31 OCTOBER 1968 K-11-68-1K

FINAL REPORT

A STUDY OF HYDROGEN SLUSH AND/OR HYDROGEN GEL UTILIZATION

Contract NAS 8-20342
(SUPPLEMENTAL PROGRAM)

VOLUME I
SATURN S-IVC MANNED MARS FLYBY VEHICLE APPLICATION STUDY

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

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CRYOGENIC STAGE PROGRAMS

LOCKHEED MISSILES & SPACE COMPANY / SUNNYVALE, CALIFORNIA
A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION

FOREWORD

The purpose of the effort conducted under this contract is to develop the analytical technology and capability required for preliminary stage design, or modifications of existing stages, to utilize hydrogen slush and/or gel propellants. Results of this study are intended to indicate the advantages or disadvantages of various slush hydrogen and/or gel systems as compared to those of cryogenic liquid systems, and to establish what basic research is necessary for preliminary design inputs.

The initial effort under this contract was directed to a 14-month analytical program which was completed in March 1967. During that program, detailed vehicle subsystems studies and three typical vehicle mission application studies were performed. The conclusion was that future use of hydrogen solid-liquid mixtures, i.e., slush, for space propulsion is both feasible and advantageous. Advantages are increased payload capabilities and reduction or elimination of hydrogen tank venting, depending upon the particular vehicle and the assigned mission. The conclusions of this study, efficiently and capably directed by Mr. A. L. Worlund, Fluid Thermal Systems Branch, Propulsion Vehicle and Engineering Laboratory, George C. Marshall Space Flight Center, were published in the final report, "A Study of Hydrogen Slush and/or Hydrogen Gel Utilization," NAS 8-20342, LMSC K-11-67-1, 2 Vols., March 11, 1967.

This initial program resulted in the conclusion that slush hydrogen is sufficiently attractive for further investigation. A supplemental program was initiated by Mr. Worlund to determine the practicality of applying slush hydrogen to NASA cryogenic-fueled vehicles under realistic conditions. In addition, it appeared of value to analyze the applicability of slush hydrogen to the Saturn S-IVC stage, a potential modification of the Saturn S-IVB for a manned Mars flyby mission. This stage and its suitability for this mission had been analyzed and reported by the Douglas Missile and Space

Systems Division of the Douglas Aircraft Company (now McDonnell Douglas). The Douglas study "Feasibility of Modifying the S-IVB Stage as an Injection Stage for Manned Planetary Flyby Missions," NAS 8-18032, DAC 57997, 2 Vols., May 1967, defined various possibilities for modifying the S-IVB stage. One attractive version, a 30-day S-IVC without a transtage associated with it, was selected to be studied under the supplemental slush hydrogen program. It was desired that the S-IVC performance and subsystems, as defined by Douglas for use with saturated liquid hydrogen, be evaluated using slush hydrogen. A performance comparison was desired, as well as identification of the impact of slush hydrogen on the S-IVC subsystems and mode of operation. This work has been completed and is reported in the Supplement Final Report, Volume I.

It was also concluded in the initial study program that experimental work was needed on a scale larger than that conducted by the Cryogenic Engineering Laboratory of the National Bureau of Standards at Boulder, Colorado, to determine the practical aspects of applying slush hydrogen to existing or new space vehicles. To perform this experimental work Lockheed provided a Cryogenic Vehicle Flight Simulator, a slush hydrogen manufacturing dewar, a slush hydrogen storage dewar, a 41.5-in. insulated flight-type propellant tank, and the necessary plumbing and controls located at the Lockheed Santa Cruz Test Base to provide realistic tools to conduct the experimental program. It was specifically intended to develop and verify recirculation as a practical ground-hold loading technique and to obtain data on the freeze-thaw manufacturing process for slush hydrogen. Other desirable data were slush storability and liquid withdrawal characteristics in a simulated space environment. The experimental program has been completed and is reported in the Supplement Final Report, Vol. II.

Throughout this program, close coordination was maintained with Mr. D. B. Chelton, Mr. D. B. Mann, and Mr. C. F. Sindt, National Bureau of Standards (NBS), Institute for Basic Standards, Cryogenics Division, where a related analytical and experimental program on slush hydrogen characteristics is in progress. Invaluable help was provided by these capable scientists.

The Lockheed work was performed under the direction of C. W. Keller, who is a Project Manager in the Propulsion Vehicle Systems group, Research and Development Division, Lockheed Missiles & Space Company. Mr. Keller was assisted in the analysis of the S-IVC Vehicle Systems by W. B. Zeber.

Key personnel at the George C. Marshall Space Flight Center were A. L. Worlund, Contract Technical Manager, and J. L. Vaniman, of the Fluid Thermal Systems Branch of the Propulsion and Vehicle Engineering Laboratory.

The overall manager of this program was Mr. Jack Suddreth, Program Manager, Liquid Propulsion Technology, Chemical Propulsion Division, NASA Office of Advanced Research and Technology.

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Section 1
INTRODUCTION AND SUMMARY

Details and results of an analytical vehicle systems study are reported in this volume. The study was one part of supplemental work performed under the basic contract (NAS 8-20342). It was undertaken to investigate the use of triplepoint liquid and slush hydrogen in the three propulsive stages of a Saturn S-IVC manned Mars fly-by orbital launch vehicle. The baseline vehicle design and analysis had been previously developed and reported by the Douglas Missiles and Space Systems Division of the Douglas Aircraft Company (now the McDonnell Douglas Company).

The primary objectives of this vehicle systems study were as follows:

- Perform detailed analysis to determine the impact of triplepoint liquid and slush hydrogen on particular S-IVC vehicle systems.
- Identify and evaluate any modifications to S-IVC vehicle system hardware and/or modes of operation required by use of triplepoint and slush hydrogen.
- Evaluate and compare performance of the S-IVC orbital launch vehicle with use of liquid hydrogen initially saturated at 11.2 N/cm^2 (16.2 psia), triplepoint liquid hydrogen, and 50-percent slush hydrogen.

These objectives were accomplished during the 20-month supplemental program by first analyzing specific vehicle systems affected by use of subcooled or slush hydrogen, and by then calculating and comparing performance in terms of obtainable manned spacecraft weight for use of hydrogen initially loaded at the three conditions of interest.

The S-IVC Orbital Launch Vehicle (OLV) configuration selected for this study by NASA MSFC consists of three modified S-IVB/V propulsive stages (designated S-IVC) arranged in tandem with a manned payload spacecraft. Each of the three fully-fueled

S-IVC stages and the manned spacecraft would be separately launched into elliptical Earth parking orbits by standard two-stage Saturn V launch vehicles over approximately a 28-day time period. The OLV component stages and spacecraft would then be individually checked out and placed in a circular assembly orbit for rendezvous, assembly, final checkout, and launch. The particular mission selected for this study by NASA MSFC is a 1975 manned Mars twilight flyby mission. All three S-IVC stages would be sequencially fired, expended, and separated from the OLV in achieving the velocity required for the trans-Mars flyby trajectory. The manned spacecraft would carry the necessary life support and secondary propulsion provisions to accomplish required midcourse, Mars flyby, and Earth atmosphere re-entry maneuvers.

1.1 STUDY RESULTS

Summarized results of the S-IVC vehicle systems study are presented in Table 1-1. These data show that manned spacecraft payload weights for the S-IVC OLV can be significantly increased by use of subcooled liquid and slush hydrogen fuels in the three propulsive stages. For example, spacecraft weights obtainable with use of triplepoint liquid and 50-percent slush are 5,285 kg (11,650 lb) and 5,829 kg (12,850 lb) greater, respectively, than that obtainable with use of 11.2 N/cm^2 (16.2 psia) saturated liquid. These respective increases in terms of percent are 6.45 and 7.12. The nominal spacecraft weight that would result from use of 11.2 N/cm^2 (16.2 psia) saturated liquid can be seen in the table to be 81,920 kg (180,600 lb).

Further inspection of the data in Table 1-1 shows that, in general, the tanked propellant weights that can be loaded into the S-IVC stages are limited to much less than the nominal capacity of the tanks which is approximately 104,328 kg (230,000 lb). This limitation is imposed by the maximum payload capability of the standard Saturn V two-stage launch vehicle which is approximately 121,111 kg (267,000 lb) injected into the assumed Earth parking orbit. It was shown in the previous contract study of the S-IVB/LASS vehicle systems (Ref. 1-1) that, where no launch vehicle capability limitation exists, it would be possible to load more total propellants with use of subcooled hydrogen and thereby realize a somewhat larger payload gain. The

Table 1-1

SUMMARY OF S-IVC MANNED MARS FLYBY VEHICLE APPLICATION STUDY RESULTS

Initial Hydrogen Condition	LH_2 Sat. at 11.2 N/cm^2 (16.2 psia)		LH_2 Sat. at Triple Point		50% Liquid-Solid Mixture	
S-IV C_1 Stage (707-hr Orbital Storage):						
Gross Earth-Launch Weight, kg (lb)	121,111	(267,000)	121,111	(267,000)	121,111	(267,000)
Total Tanked Propellant Weight, kg (lb)	95,254	(209,995)	95,215	(209,910)	95,037	(209,518)
Total Tanked Hydrogen Weight, kg (lb)	19,736	(43,510)	21,241	(46,828)	20,124	(44,364)
Optimum Main Stage Mixture Ratio, O/H by Weight	5.5		4.2		4.2	
Optimum H_2 Tank Sidewall Insulation Thickness, cm (in.)	6.35	(2.5)	6.35	(2.5)	6.35	(2.5)
Optimum Common Bulkhead Insulation Thickness, cm (in.)	15.2	(6.0)	15.2	(6.0)	15.2	(6.0)
Total Hydrogen Vented in Earth Orbit, kg (lb)	3,676	(8,104)	1,486	(3,277)	145	(320)
S-IV C_2 Stage (686-hr Orbital Storage):						
Gross Earth-Launch Weight, kg (lb)	119,969	(264,482)	121,111	(267,000)	121,111	(267,000)
Total Tanked Propellant Weight, kg (lb)	94,280	(207,849)	95,385	(210,285)	95,268	(210,027)
Total Tanked Hydrogen Weight, kg (lb)	19,877	(43,820)	21,508	(47,416)	20,699	(45,632)
Optimum Main Stage Mixture Ratio, O/H by Weight	5.5		4.2		4.2	
Optimum H_2 Tank Sidewall Insulation Thickness, cm (in.)	6.35	(2.5)	6.35	(2.5)	6.35	(2.5)
Optimum Common Bulkhead Insulation Thickness, cm (in.)	8.89	(3.5)	8.89	(3.5)	8.89	(3.5)
Total Hydrogen Vented in Earth Orbit, kg (lb)	3,906	(8,611)	1,677	(3,696)	703	(1,549)
S-IV C_3 Stage (62-hr Orbital Storage):						
Gross Earth-Launch Weight, kg (lb)	121,111	(267,000)	121,111	(267,000)	121,111	(267,000)
Total Tanked Propellant Weight, kg (lb)	98,010	(216,072)	98,124	(216,323)	98,037	(216,130)
Total Tanked Hydrogen Weight, kg (lb)	19,777	(43,600)	20,775	(45,801)	20,759	(45,764)
Optimum Main Stage Mixture Ratio, O/H by Weight	4.784		4.2		4.2	
Optimum H_2 Tank Sidwall Insulation Thickness, cm (in.)	3.81	(1.5)	2.54	(1.0)	2.54	(1.0)
Optimum Common Bulkhead Insulation Thickness, cm (in.)	0		0		0	
Total Hydrogen Vented in Earth Orbit, kg (lb)	993	(2,189)	0		0	
Orbital Launch Vehicle (1975 Mars Twilight Mission):						
Gross Assembled Orbital Launch Weight, kg (lb)	392,106	(864,431)	404,726	(892,253)	407,320	(897,971)
Payload Spacecraft Weight, kg (lb)	81,920	(180,600)	87,205	(192,250)	87,749	(193,450)
Increase in Payload Weight kg (lb)	0 (ref)		5,285	(11,650)	5,829	(12,850)
%	0 (ref)		6.45		7.12	

additional propellant that could be loaded and used would, of course, be limited by the maximum capacity of the S-IVC hydrogen tank and the minimum permissible engine mixture ratio which was assumed to be 4.2 to 1 (O_2 to H_2 by weight). In this study of the S-IVC OLV, as in the previous study of the S-IVB/LASS vehicle, it can be seen that it is more advantageous to reduce the engine mixture ratio where subcooled hydrogen is used.

Results of the study show, in addition, that optimum insulation thicknesses are the same for use of hydrogen at all initial conditions of interest in the S-IVC$_1$ and S-IVC$_2$ stages, but that the optimum thickness decreases with subcooling in the S-IVC$_3$ stage. Although venting of hydrogen could be very significantly reduced with use of subcooling, it could not be eliminated with optimum insulation thicknesses in either the S-IVC$_1$ or S-IVC$_2$ stages, but could be eliminated with optimized insulation in the S-IVC$_3$ stage.

1.2 CONCLUSIONS

The major conclusions obtained from the study are as follows:

- Use of triplepoint liquid or slush hydrogen rather than 16.2-psia-saturated hydrogen in the S-IVC OLV propulsive stages can provide approximately 6.5 to 7.1 percent greater manned spacecraft weight capability.
- Venting of hydrogen can be significantly reduced with use of subcooling in both the S-IVC$_1$ and S-IVC$_2$ stages, and can be completely eliminated in the S-IVC$_3$ stage.
- Only relatively minor modifications would be required in S-IVC system hardware and modes of operation to load and use subcooled liquid and slush hydrogen.

Section 2
SATURN S-IVC SYSTEM STUDIES

2.1 VEHICLE/MISSION CHARACTERISTICS

An Earth-orbital launch vehicle (OLV) applied to a 1975 manned Mars twilight flyby mission was specified by NASA MSFC as the basis for system studies during this part of the program. The particular OLV configuration selected by MSFC for this mission study consists of three modified S-IVB propulsive stages (designated S-IVC) arranged in tandem behind a manned payload spacecraft (see Fig. 2-1). Each of the S-IVC stages and the spacecraft would be separately launched from earth by standard two-stage-to-orbit Saturn V launch vehicles. The S-IVC stages would be launched with the necessary propellants, pressurants, and power supplies required for the mission.

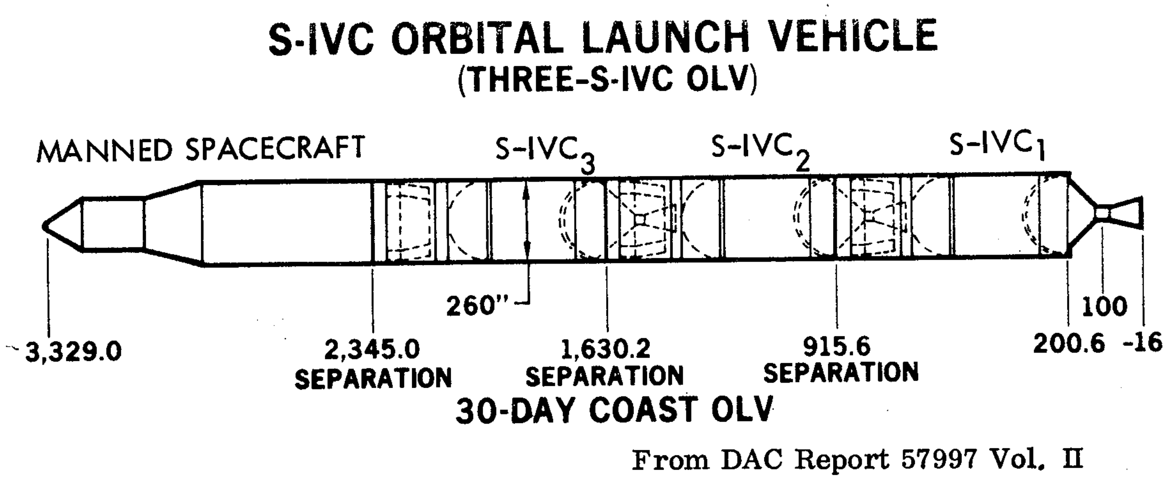
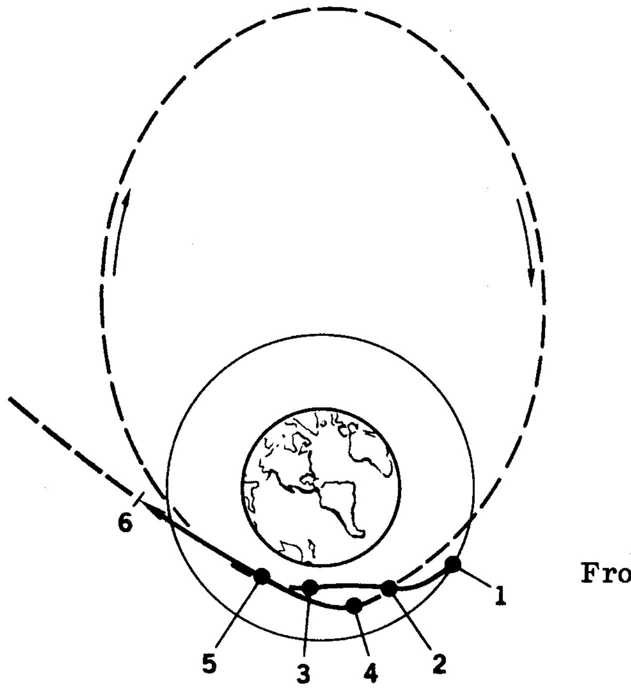


Fig. 2-1 S-IVC Orbital Launch Vehicle

Similarly, the manned spacecraft would be launched with the crew and all required system and life support supplies on board. Rendezvous, assembly, and checkout of the OLV stages and the spacecraft would then be performed in an Earth parking (assembly) orbit prior to initiation of the trans-Mars launch. All three S-IVC stages would finally be expended, separated, and jettisoned in sequence in order to achieve the trans-Mars injection velocity.

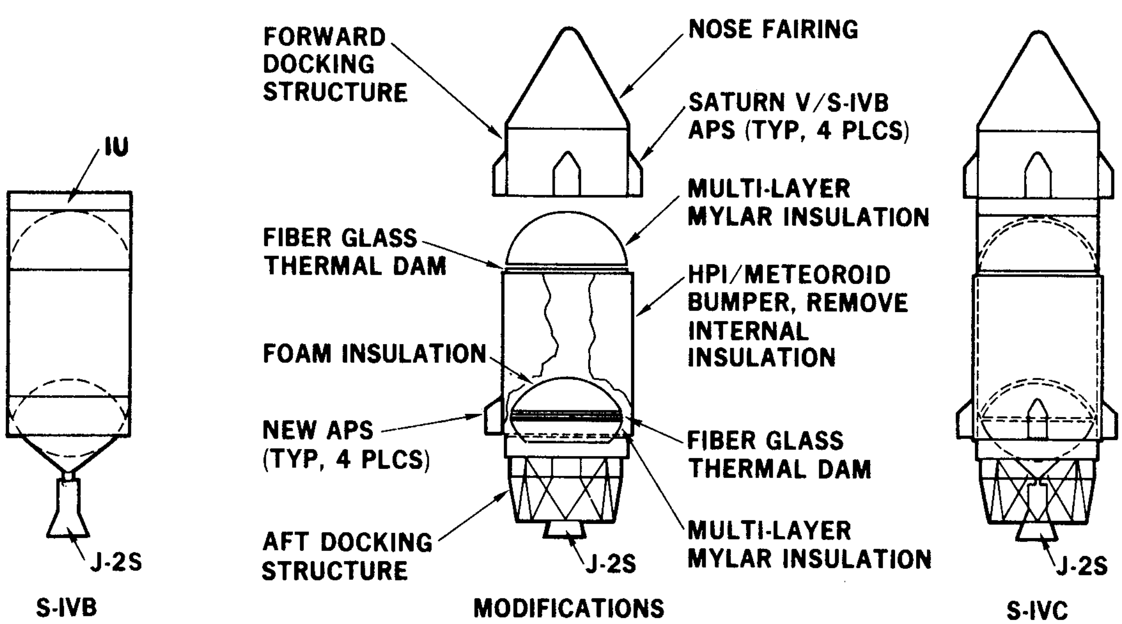
The Douglas Missiles and Space Systems Division of the Douglas Aircraft Company (now the McDonnell Douglas Corporation) originally investigated this OLV concept in a NASA-sponsored program completed in May 1967 (Ref. 2-1). Two promising S-IVC stage configurations were identified and investigated in the Douglas study. One of these was a minimum-modification version of an S-IVB/V with an orbital lifetime capability of 110 hr; the other was a long-term coast version with a nominal 30-day orbital lifetime capability. Douglas also investigated other configuration variations including use of auxiliary propulsion located in separate transtages for each S-IVC stage to provide the relatively small velocity increments needed to inject into the Earth parking orbit, and to adjust that orbit for rendezvous with other OLV components. The alternative to use of the transtages would be use of the S-IVC primary propulsion systems to provide these early orbit impulse requirements as well as the trans-Mars injection requirement. The 30-day orbital lifetime version, without a transtage, was found to be the most advantageous by Douglas, and, consequently, this version was selected as the only configuration candidate for this study. Figure 2-2 shows the S-IVC orbital launch mode and Fig. 2-3 shows the basic configuration as compared to an S-IVB.

The basic concept of the nominal 30-day orbital S-IVC stage is shown in Fig. 2-4. It is 6.6 m (260 in.) in diameter, and approximately 17.85 m (703 in.) in length from the forward skirt separation plane to the J-2S engine exit plane. Its dry weight ranges from approximately 13,154 kg (29,000 lb) to approximately 14,062 kg (31,000 lb), depending on insulation thicknesses and pressurization requirements associated with each of the three OLV stages. The basic shapes, dimensions, and volumes of the tankage were not changed from the existing S-IVB configuration (e.g., SA-504 stage),



From DAC Report 57997 Vol. II

Fig. 2-2 S-IVC Orbital Launch Mode



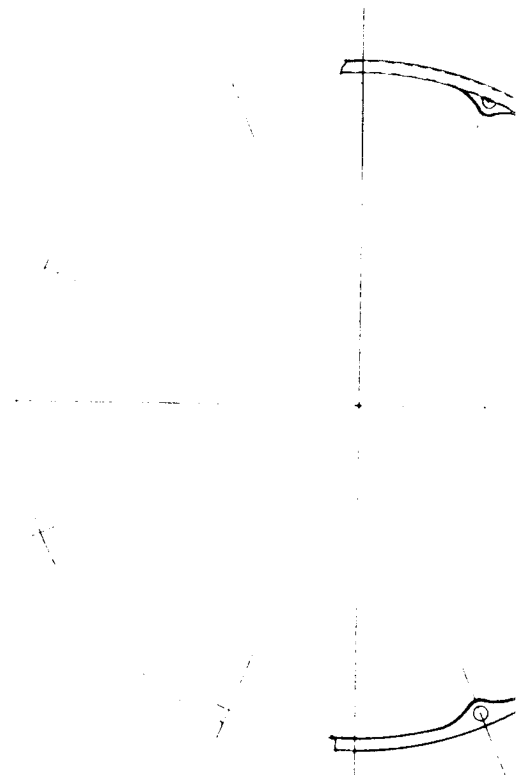
From DAC Report 57997 Vol. II

Fig. 2-3 Comparison of S-IVB and 30-Day, No Transtage S-IVC Configurations except by removal of the internal foam insulation from the hydrogen tank sidewall, and by addition of foam insulation to the hydrogen side of the common tank bulkhead. Primary propellant loadings for the three OLV stages range from approximately 95,256 kg (210,000 lb) to approximately 97,978 kg (216,000 lb), although the total propellant capacity of the tankage is approximately 104,328 kg (230,000 lb).

A typical weight breakdown for the S-IVC stage (as derived and reported by Douglas) is given in Table 2-1. This table identifies the items that are removed from the S-IVB and the items that are added to transfer this vehicle into a 30-day S-IVC configuration using 11 N/cm^2 (16.2 psia) saturated liquid hydrogen.

The mission operating procedures have an impact upon the slush hydrogen analysis performed in this study. Although the three basic S-IVC stages used in this mission are very similar*, they differ one from the other in their mode of utilization. Each S-IVC stage is injected into a 185.3 km (100 nm) by 488.3 km (263.5 nm) elliptical Earth orbit by the standard Saturn V S-IC and S-II stage launch vehicle. This elliptical orbit geometry was selected to provide phasing capability with the 488.3 km (263.5 nm) circular assembly orbit. Prior to circularization of the orbit geometry and docking, each S-IVC stage will be checked out in the elliptical orbit. After the satisfactory checkout of each S-IVC stage and the spacecraft, docking and assembly of the entire OLV is then performed in the circular assembly orbit. Checkout is once more accomplished and the launch into the trans-Mars trajectory is effected. For the 3-stage configuration, the first stage, designated S-IVC$_1$, is completely expended, separated, and followed immediately by a firing of the second stage, (S-IVC$_2$), in which approximately 25 percent of its propellants are expended. A 185.3/7413 km (100/4000 nm) elliptical Earth orbit having about a 3-hr period results from these two firings of the S-IVC$_1$ and the S-IVC$_2$. Near perigee the S-IVC$_2$ stage is restarted, and, after

*The three stages differ only in insulation thicknesses, propellant management instrumentation/plumbing requirements, and pressurization system requirements.



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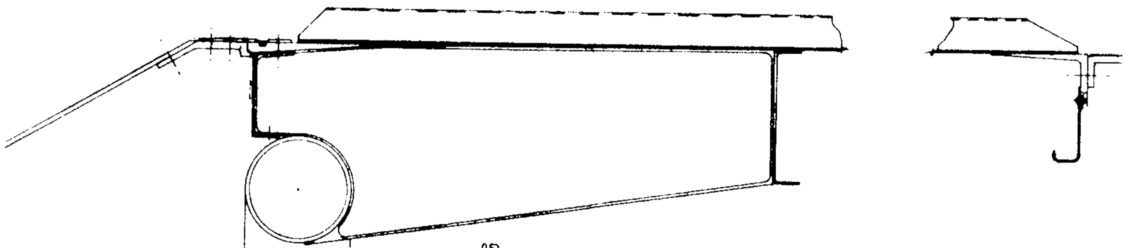

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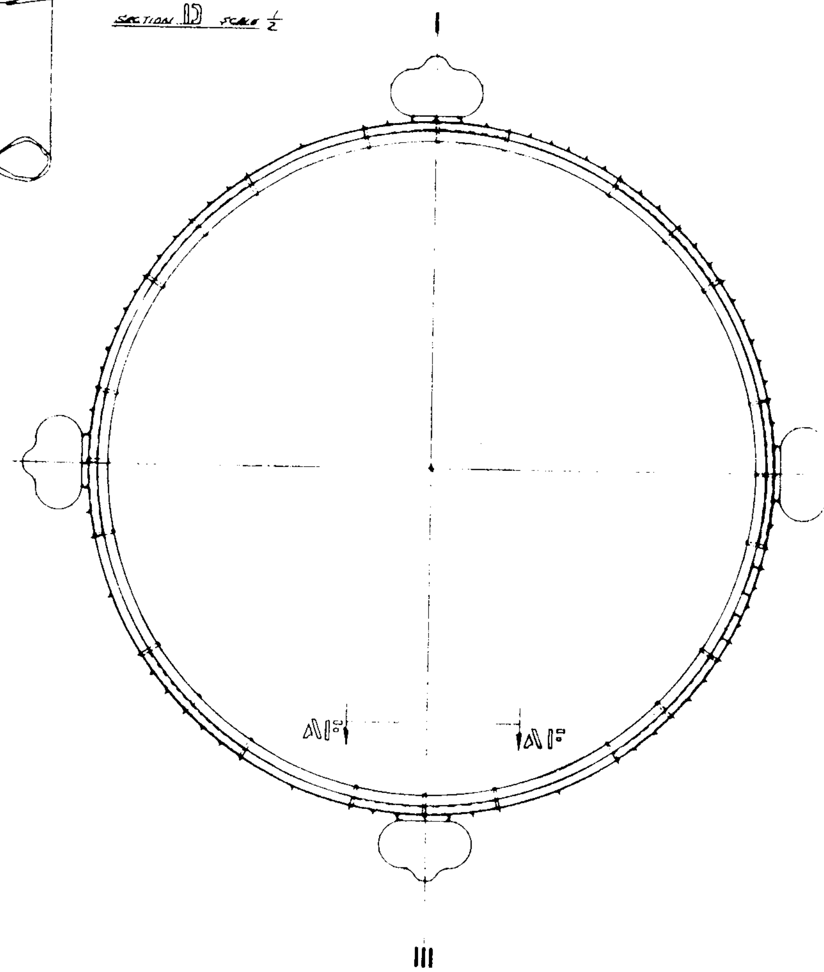

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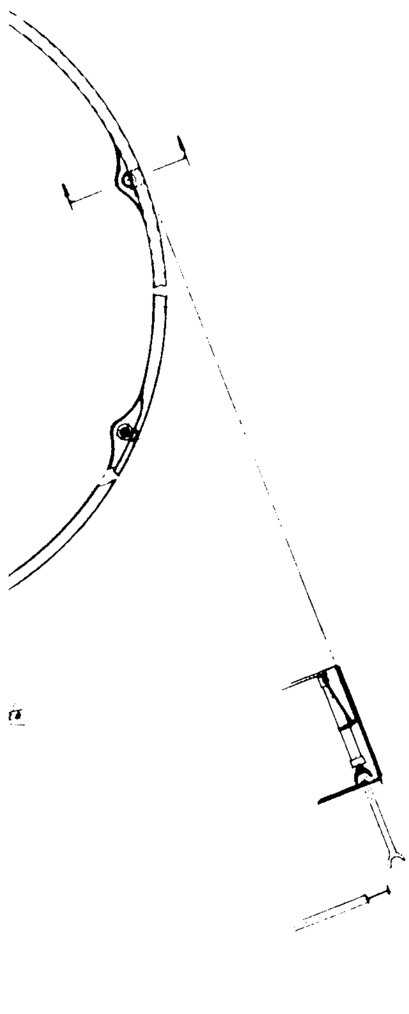

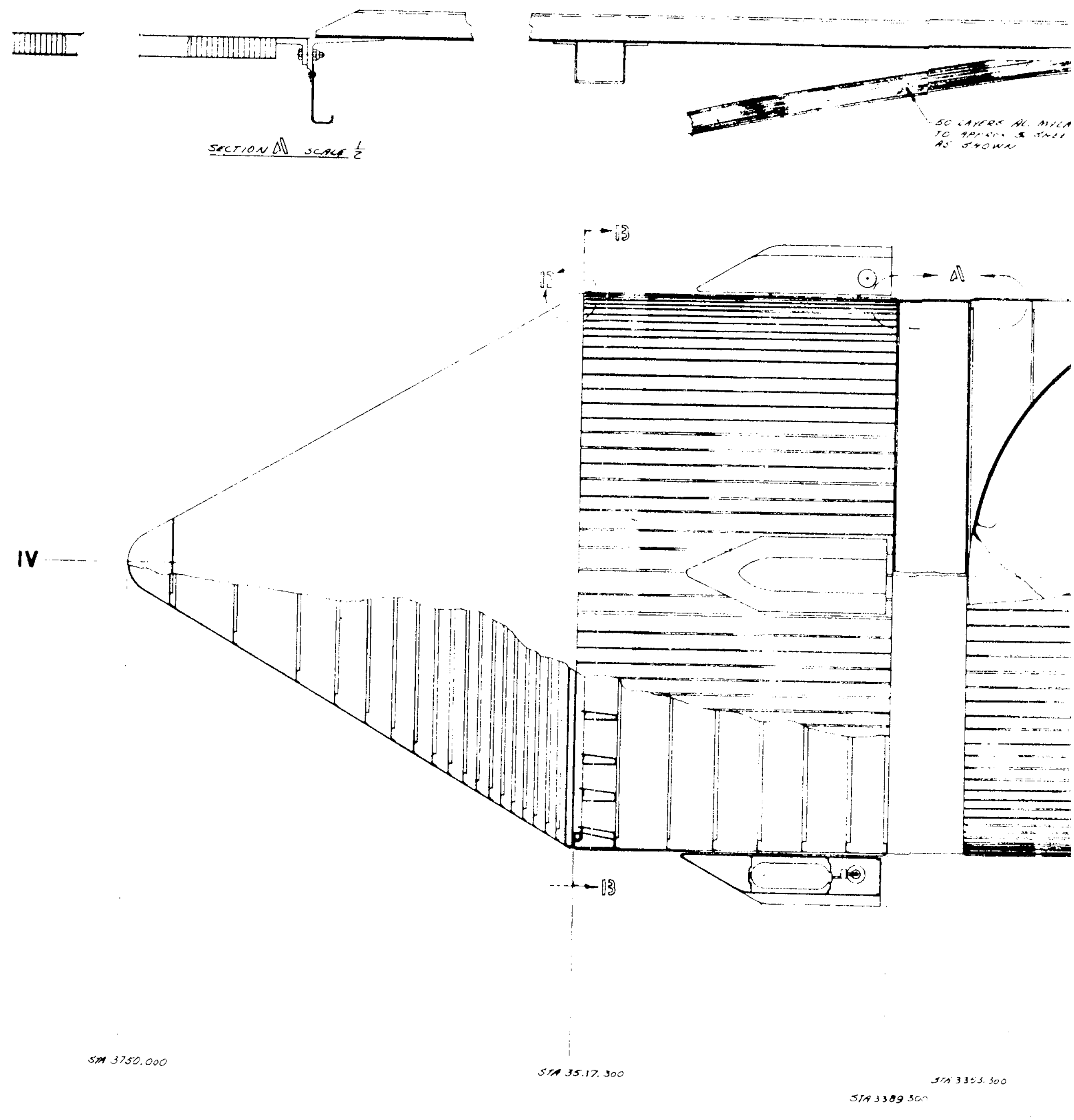
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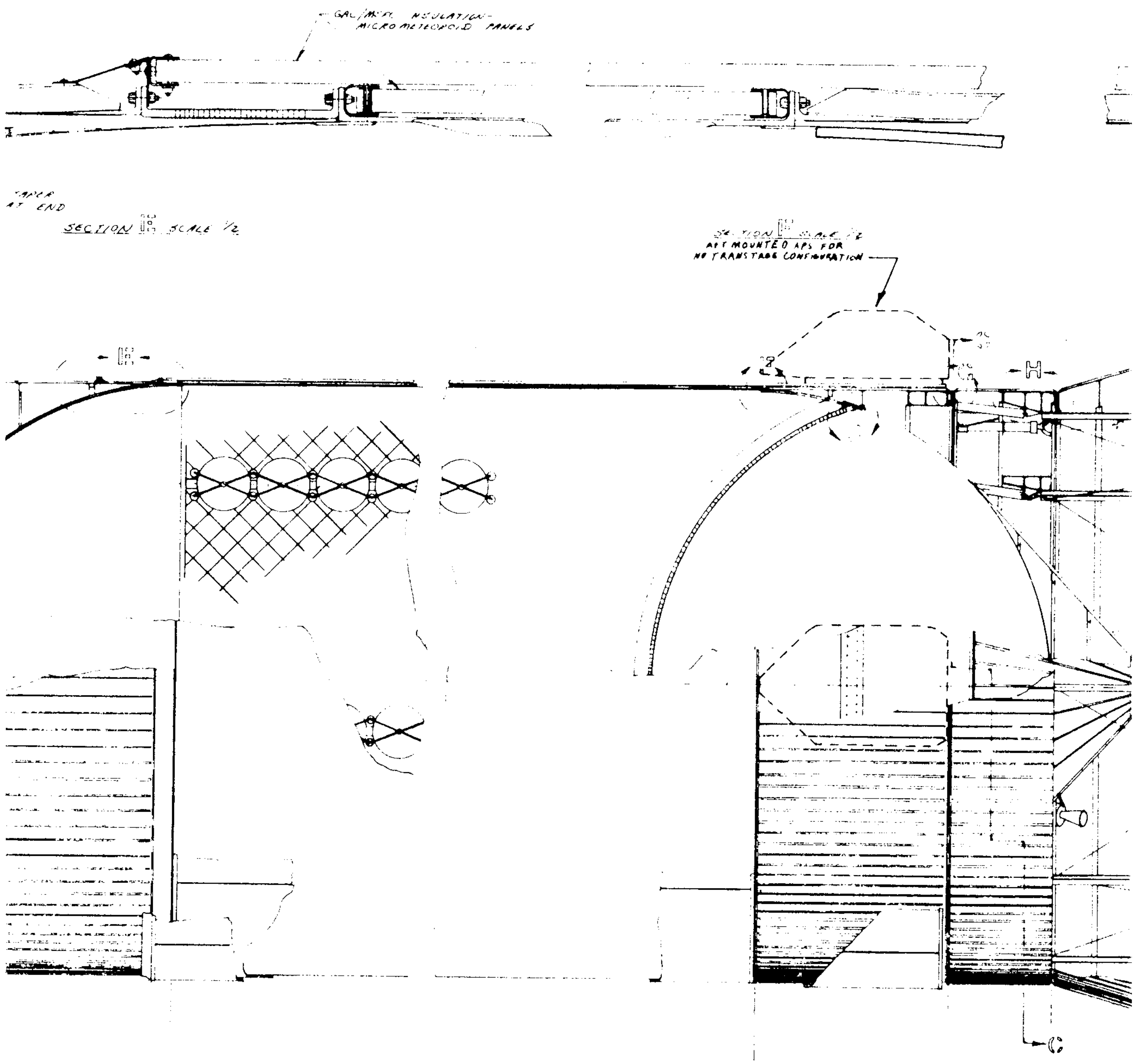


30 DAY ORBITAL CONFIGURATION

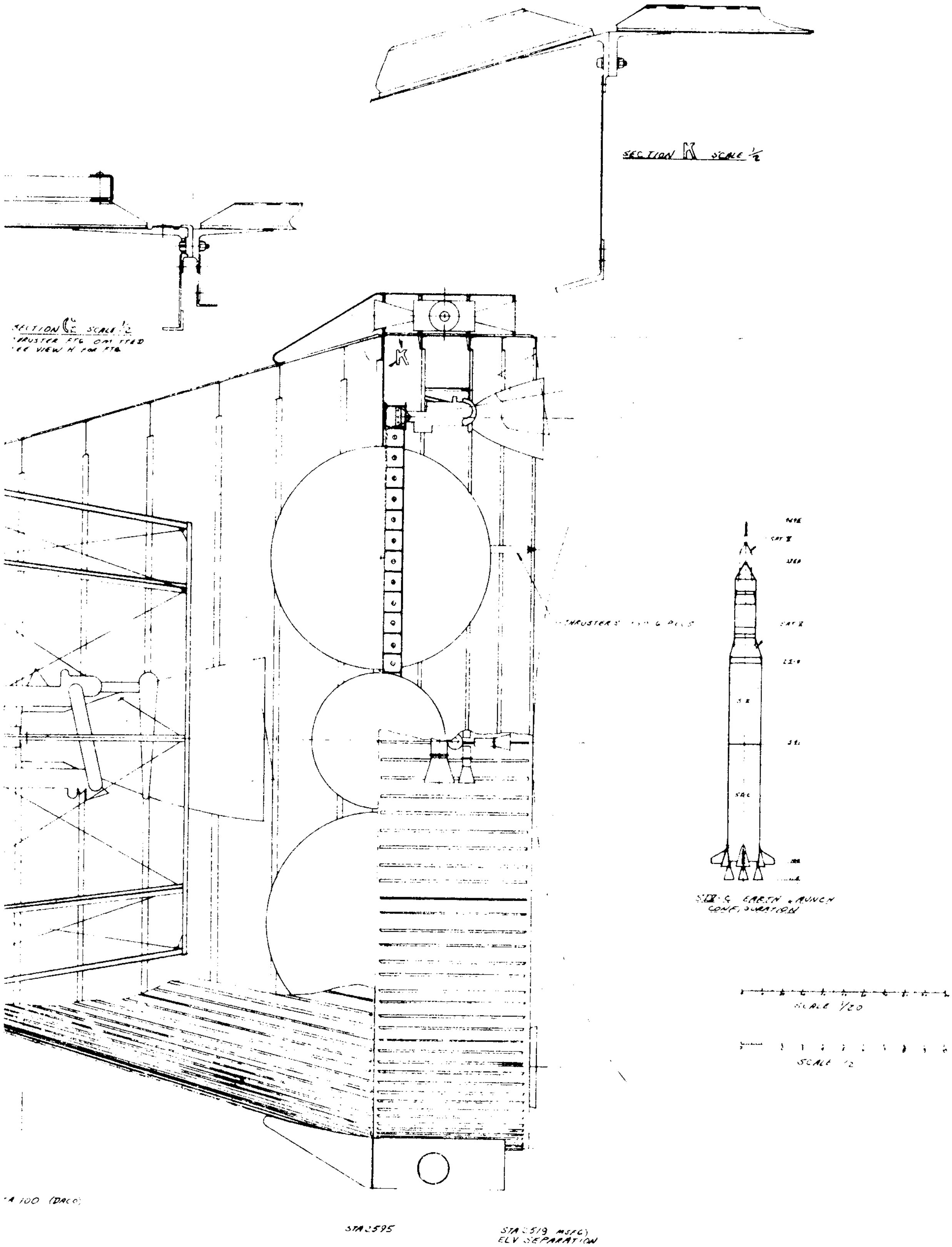


Fig. 2-4 Inboard Profile of 30-Day, No Transtage S-IVC Stage (From DAV Report 57997, Vol. II)

Table 2-1

TYPICAL WEIGHT BREAKDOWN FOR 30-DAY, NO TRANSTAGE S-IVC CONFIGURATION

	Weight	
	(kg)	(lb)
Dry stage (SA504 and subsequent)	11,284	24,876
Remove:		
Batteries and mounts	- 376	- 830
APS modules	- 388	- 855
Ullage rockets	- 91	- 200
Chilldown and purge system	- 130	- 287
Miscellaneous engine systems	- 22	- 48
Internal insulation	- 629	-1,386
Add:		
Aft skirt APS modules	+ 36	+ 80
J-2S engine	- 112	- 246
Common bulkhead insulation	+ 653	+1,440
Forward heat block	+ 106	+ 233
Forward dome external insulation	+ 34	+ 74
Power system	+1,557	+3,432
Common dome heat block	+ 12	+ 26
External insulation and bumper	+ 758	+1,672
Aft dome insulation	+ 4	+ 9
Forward docking structure	+ 772	+1,702
Aft docking structure	+ 604	+1,332
Vehicle dry weight	14,072	31,024

all propellants are expended, the stage is then separated. The third S-IVC$_3$ stage is then started and thrusting continued until all propellants are depleted. At this point, trans-Mars injection velocity has been reached. This mission profile can be diagrammed in real time to provide mission increments for detailed S-IVC stage analysis. This was done and is shown in Fig. 2-5. Because of the above described mode of operation, the heating rates into the propellant tankage will vary since each of the S-IVC stages is exposed to varying environments for variable time periods. In addition, the manner of usage is slightly different, since the S-IVC$_2$ employs one restart. Therefore, when analyzing the S-IVC for applicability of subcooled triple point hydrogen or slush hydrogen, it is necessary to calculate the thermal mission environment for each individual S-IVC stage throughout its mission life.

Figure 2-6 is representative of the ascent profile used to place the S-IVC stages into the Earth assembly orbit prior to performing orbital launch. The use and/or boiloff of the hydrogen propellant during this ascent flight profile is partially dependent upon the propellants tanked on the ground and partially dependent upon the heating factors and operational modes of the pertinent vehicle subsystems during ascent flight. The tanked propellant weights for the S-IVC$_1$, S-IVC$_2$, and S-IVC$_3$ stages have been determined and are summarized in Tables 2-2 and 2-3.

These tables include tanked propellant weights for saturated 11 N/cm^2 (16.2 psia) liquid hydrogen, for triple-point liquid hydrogen, and for liquid hydrogen containing 50 percent solid crystalline hydrogen (slush).

Details and results of subsystem studies conducted during the overall analysis of the S-IVC vehicle are presented in the paragraphs that follow.

2.2. PROPELLANT MANAGEMENT SYSTEM

Consideration was given to three particular aspects of the propellant management system during the overall study. These aspects were (1) tank fill and groundhold requirements, (2) system tolerance effects, and (3) instrumentation requirements for mass and quality measurements. In general, the results obtained in considering

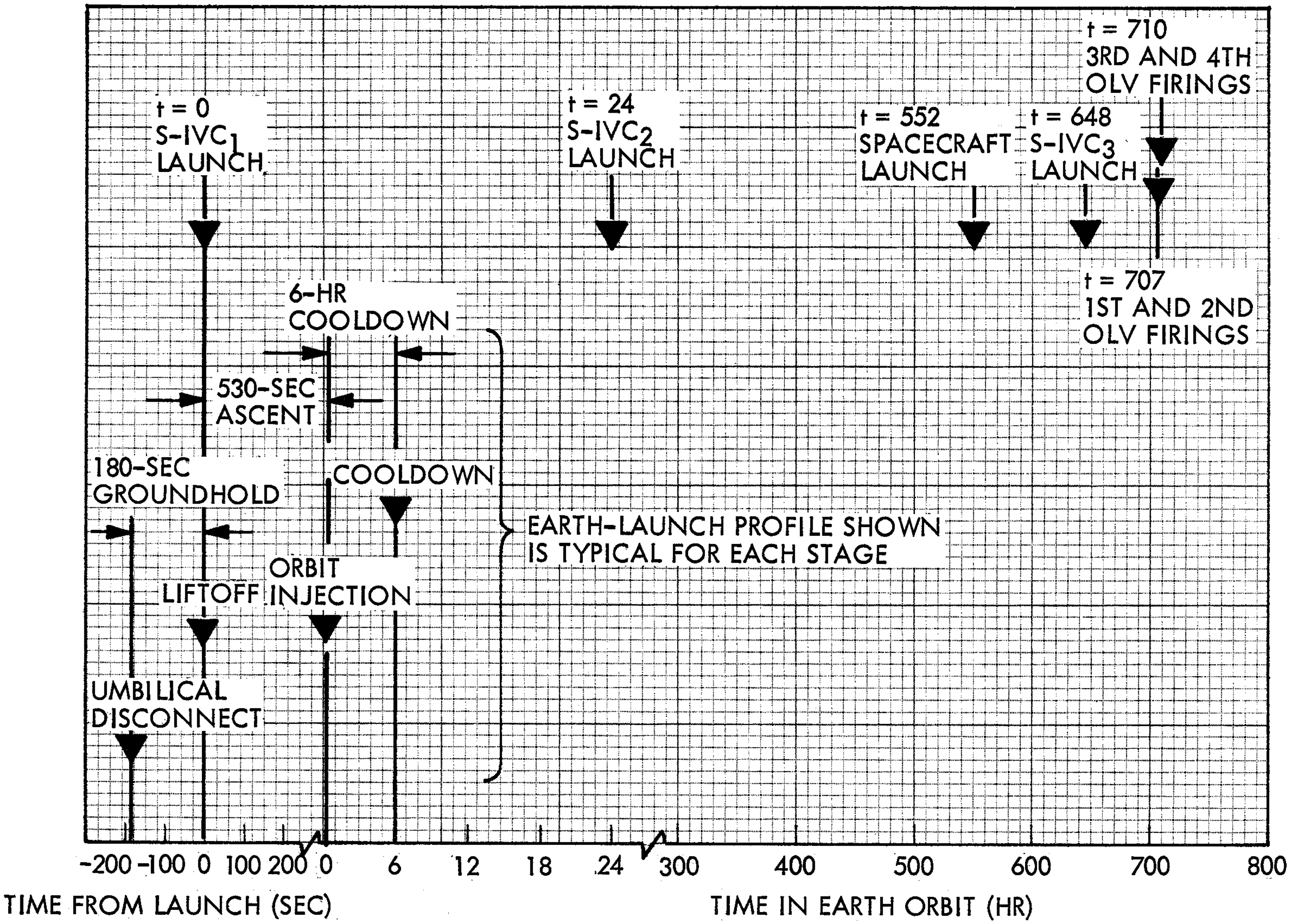
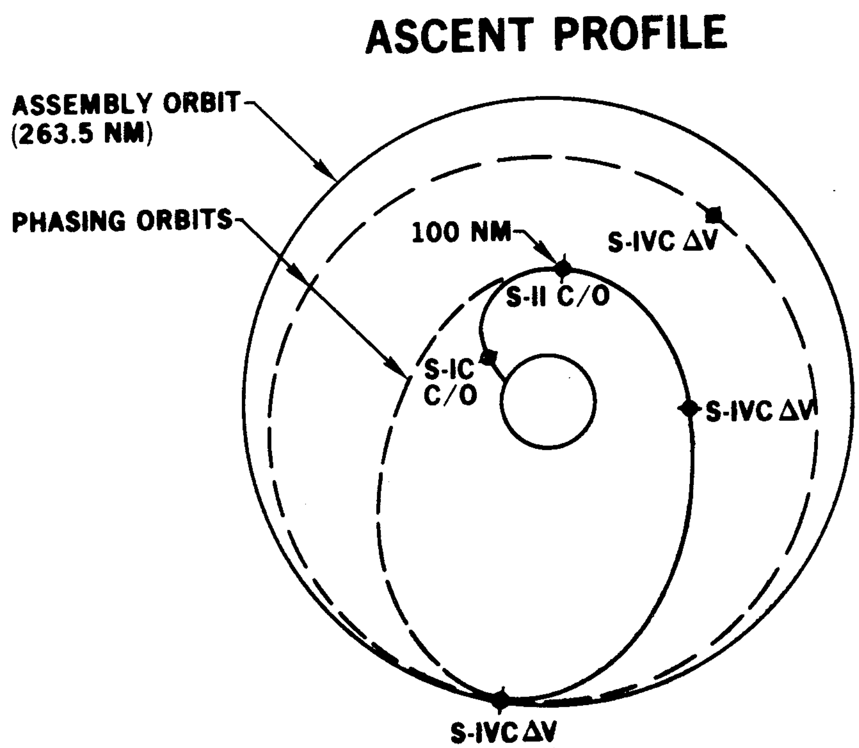


Fig. 2-5 Earth-Launch and Orbital-Launch Mission Profiles for S-IVC Flyby Vehicle



From DAC Report 57997 Vol. II

Fig. 2-6 S-IVC Earth Launch Mode

Table 2-2

SUMMARY OF TANKED PROPELLANT WEIGHTS FOR S-IVC$_1$ AND S-IVC$_2$ STAGES

Description of Propellant Usage	Initial Hydrogen Condition											
	LH_2 Sat. at 11.2 N/cm^2 (16.2 psia)				LH_2 Sat. at T.P.				50 Percent Liquid-Solid Mixture			
	O_2 kg (lb)	H_2 kg (lb)	Total kg (lb)	Mixture Ratio	O_2 kg (lb)	H_2 kg (lb)	Total kg (lb)	Mixture Ratio	O_2 kg (lb)	H_2 kg (lb)	Total kg (lb)	Mixture Ratio
S-IV C$_1$ Stage:												
Total Transient and Idle-Mode Impulse Propellants	2,258 (4,978)	1,973 (4,348)	4,231 (9,326)		2,258 (4,978)	1,973 (4,348)	4,231 (9,326)		2,258 (4,978)	1,973 (4,348)	4,231 (9,326)	
Mainstage Impulse for Orbit Circularization	1,617 (3,564)	294 (648)	1,911 (4,212)	5.5	1,235 (2,722)	294 (648)	1,529 (3,370)	4.2	1,235 (2,722)	294 (648)	1,529 (3,370)	4.2
Mainstage Impulse for 1st OLV Firing	70,564 (155,565)	12,830 (28,285)	83,394 (183,850)	5.5	69,403 (153,004)	16,525 (36,430)	85,928 (189,434)	4.2	70,342 (155,076)	16,748 (36,923)	87,090 (191,999)	4.2
Total Vented Propellants	912 (2,010)	3,676 (8,104)	4,588 (10,114)		912 (2,010)	1,486 (3,277)	2,398 (5,287)		912 (2,010)	145 (320)	1,057 (2,330)	
P. U. Reserves and Residuals	167 (368)	964 (2,125)	1,131 (2,493)		167 (368)	964 (2,125)	1,131 (2,493)		167 (368)	964 (2,125)	1,131 (2,493)	
Total Tanked Propellants	75,518 (166,485)	19,737 (43,510)	95,255 (209,995)		73,975 (163,082)	21,242 (46,828)	95,217 (209,910)		74,914 (165,154)	20,124 (44,364)	95,038 (209,518)	
S-IV C$_2$ Stage:												
Total Transient and Idle-Mode Impulse Propellants	2,559 (5,642)	2,130 (4,697)	4,689 (10,339)		2,559 (5,642)	2,130 (4,697)	4,689 (10,339)		2,559 (5,642)	2,130 (4,697)	4,689 (10,339)	
Mainstage Impulse for Orbit Circularization	1,617 (3,564)	294 (648)	1,911 (4,212)	5.5	1,235 (2,722)	294 (648)	1,529 (3,370)	4.2	1,235 (2,722)	294 (648)	1,529 (3,370)	4.2
Mainstage Impulse for 2nd OLV Firing	17,301 (38,141)	3,146 (6,935)	20,447 (45,076)	5.5	17,265 (38,062)	4,111 (9,062)	21,376 (47,124)	4.2	17,438 (38,443)	4,152 (9,153)	21,590 (47,596)	4.2
Mainstage Impulse for 3rd OLV Firing	51,903 (114,424)	9,437 (20,804)	61,340 (135,228)	5.5	51,794 (114,185)	12,332 (27,188)	64,126 (141,373)	4.2	52,314 (115,330)	12,456 (27,460)	64,770 (142,790)	4.2
Total Vented Propellants	857 (1,890)	3,906 (8,611)	4,763 (10,501)		857 (1,890)	1,677 (3,696)	2,534 (5,586)		857 (1,890)	703 (1,549)	1,569 (3,439)	
P. U. Reserves and Residuals	167 (368)	964 (2,125)	1,131 (2,493)		167 (368)	964 (2,125)	1,131 (2,493)		167 (368)	964 (2,125)	1,131 (2,493)	
Total Tanked Propellants	74,404 (164,029)	19,877 (43,820)	94,281 (207,849)		73,877 (162,869)	21,508 (47,416)	95,385 (210,285)		74,570 (164,395)	20,699 (45,632)	95,268 (210,027)	

Table 2-3

SUMMARY OF TANKED PROPELLANT WEIGHTS FOR S-IVC_3 STAGE

~~SUMMARY OF~~ TANKED PROPELLANT WEIGHTS FOR S-IV C_3 STAGE

Description of Propellant Usage	Initial Hydrogen Condition											
	LH_2 Sat. at 11.2 N/cm^2 (16.2 psia)				LH_2 Sat. at T.P.				50 Percent Liquid-Solid Mixture			
	O_2 kg (lb)	H_2 kg (lb)	Total kg (lb)	Mixture Ratio	O_2 kg (lb)	H_2 kg (lb)	Total kg (lb)	Mixture Ratio	O_2 kg (lb)	H_2 kg (lb)	Total kg (lb)	Mixture Ratio
S-IV C_3 Stage:												
Total Transient and Idle-Mode Impulse Propellants	2,258 (4,978)	1,973 (4,348)	4,231 (9,326)		2,258 (4,978)	1,973 (4,348)	4,231 (9,326)		2,258 (4,978)	1,973 (4,348)	4,231 (9,326)	
Mainstage Impulse for Orbit Circularization	1,406 (3,100)	294 (648)	1,700 (3,748)	4.784	1,235 (2,722)	294 (648)	1,529 (3,370)	4.2	1,235 (2,722)	294 (648)	1,529 (3,370)	4.2
Mainstage Impulse for 4th OLV Firing	74,402 (164,026)	15,554 (34,290)	89,956 (198,316)	4.784	73,689 (162,454)	17,545 (38,680)	91,234 (201,134)	4.2	73,618 (162,298)	17,528 (38,643)	91,146 (200,941)	4.2
Total Vented Propellants	0	993 (2,189)	993 (2,189)		0	0	0		0	0	0	
P.U. Reserves and Residuals	167 (368)	964 (2,125)	1,131 (2,493)		167 (368)	964 (2,125)	1,131 (2,493)		167 (368)	964 (2,125)	1,131 (2,493)	
Total Tanked Propellants	78,233 (172,472)	19,778 (43,600)	98,011 (216,072)		77,349 (170,522)	20,776 (45,801)	98,125 (216,323)		77,278 (170,366)	20,759 (45,764)	98,037 (216,130)	

these aspects for the S-IVC stages were similar to those obtained in the previous contract study for the S-IVB (Ref. 2-2). In that study the existing S-IVB propellant management system design was reviewed to determine its approximate compatibility with use of subcooled liquid and slush hydrogen. Briefly, it was found that particular components of the system that would require detailed analysis and modification are the following: (1) engine suction line screen and baffling, (2) temperature sensors, (3) quality meters, (4) recirculation disconnect, (5) recirculation control valve, (6) recirculation liquid-return line, (7) additional capacitors on the LH_2 mass probe, (8) chilldown pump screen, (9) additional three-way valve for chilldown pump circulation, header, and control, (10) GHe/GH_2 scavenge system, and (11) improved chilldown pump mounting.

2.2.1 Tank Fill and Groundhold Requirements

The tank fill and groundhold requirements for use of triple-point liquid and 50-percent slush hydrogen in the three S-IVC stages were determined using the relationships developed for steady-state recirculation during the initial contract study (Ref. 2.3). Results of this analysis are presented in Table 2-4. Loading and topping requirements for use of saturated liquid hydrogen in these stages is not shown since these requirements are identical for the existing S-IVB and the proposed S-IVC stages.

Inspection of the data presented in Table 2-4 shows that the maximum continuous flow requirement is 16,193 kg/hr (35,699 lb/hr) of 50-percent slush to maintain triple-point liquid or any slush quality in the $S\text{-}IVC_3$ tank. This flowrate is equivalent to a flow velocity of approximately 3.061 m/sec (10.047 ft/sec) through the existing 15.24-cm (6-in.) diameter fill line.

2.2.2 System Tolerance Effects

Significant payload penalties will result from instrumentation and design tolerances associated with (1) loaded hydrogen quantity, (2) loaded slush hydrogen quality, (3) hydrogen quantity available in flight, (4) ground-vent pressure, (5) flight-vent

Table 2-4

SUMMARY OF S-IVC GROUNDHOLD RECIRCULATION REQUIREMENTS

Stage and Loading Parameter	Initial Hydrogen Condition			
	Triple-Point LH_2		50-Percent SH_2	
S-IVC$_1$ Stage:				
Groundhold Heat Load, w (Btu/hr)	83,616	(285,540)	83,616	(285,540)
Tanked H_2 Weight, kg (lb)	21,241	(46,828)	20,124	(44,364)
Initial Fill Volume, m^3 (ft^3)	275.8	(9,740)	246.8	(8,716)
*Steadystate Recirculation Flowrate, kg/hr (lb/hr)	10,361	(22,842)	10,361	(22,842)
S-IVC$_2$ Stage:				
Groundhold Heat Load, w (Btu/hr)	83,703	(285,840)	83,703	(285,840)
Tanked H_2 Weight, kg (lb)	21,508	(47,416)	20,335	(44,830)
Initial Fill Volume, m^3 (ft^3)	279.3	(9,862)	249.4	(8,807)
*Steadystate Recirculation Flowrate, kg/hr (lb/hr)	10,373	(22,868)	10,373	(22,868)
S-IVC$_3$ Stage:				
Groundhold Heat Load, w (Btu/hr)	130,674	(446,240)	130,674	(446,240)
Tanked H_2 Weight, kg (lb)	20,775	(45,801)	20,759	(45,764)
Initial Fill Volume, m^3 (ft^3)	269.8	(9,526)	254.6	(8,991)
*Steadystate Recirculation Flowrate, kg/hr (lb/hr)	16,193	(35,699)	16,193	(35,699)

*Based on an average slush supply quality of 50 percent at the tank inlet.

pressure, and (6) total heat load on the hydrogen tank. Equations which relate payload penalty magnitude to tolerance magnitude for these hydrogen tank variables were developed and evaluated for the S-IVB/LASS* vehicle during the initial contract study (Ref. 2.4). It was shown then that approximately 10-percent payload penalties would result from the root-mean-square combination of state-of-the-art tolerances on each of these variables for that vehicle. No further payload penalty analysis was performed for the S-IVC vehicle stages since it was estimated that the net effect for this vehicle would be less than that previously determined for the S-IVB/LASS vehicle. The payload penalty depends primarily on the tolerance of hydrogen quantity available in flight, and much less on loaded hydrogen quantity, total heat load on the hydrogen tank, slush quality, flight-vent pressure, and ground-vent pressure, in that order.

2.2.3 Instrumentation and Plumbing Modifications

It was determined during the previous contract study that significant S-IVB instrumentation and control component modifications would be required where subcooled liquid and slush hydrogen are used rather than atmospheric saturated liquid (Ref. 2.5). During the analysis of the present S-IVC study, similar modifications were assumed to determine the inert weight differences required for each stage.

For use of triple-point liquid, these modifications include the following: (1) replacement or recalibration of temperature sensors, and (2) replacement or recalibration of capacitance probes.

For use of slush hydrogen, the additional modifications required include: (1) installation of a liquid recirculation line, control valve, and disconnect; (2) replacement or recalibration of temperature and capacitance sensors; (3) installation of gamma-or beta-source nuclear densitometers; and (4) installation of a screen near the tank outlet to filter and retain solid hydrogen particles in the tank during expulsion of liquid for engine firings.

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*Lunar Applications of a Spent S-IVB Stage

2.3 PROPULSION SYSTEM

Another factor considered in the analysis of the Orbital Launch Vehicle component stages is the main propulsion engine assumed to be used with the S-IVC. This engine is the North American Rockwell (Rocketdyne) J-2S engine (Ref. 2.6). Its operating characteristics with saturated liquid hydrogen and subcooled or slush hydrogen are given in Table 2-5. It must be noted herein for the purposes of this study that subcooled hydrogen will affect the mixture ratio, the specific impulse, and consequently, the thrust of the J-2S engine. These variations from normal for saturated hydrogen are given in Fig. 2-7. These variations in engine performance were used in obtaining the results shown later in this study. For example, adjustments should be made in the engine operation due to the nature of the initial hydrogen conditions and these adjustments, in turn, will affect the propellant weights required for transient and idle-mode impulse. The variation in these propellant weights are calculated and shown in Table 2-6. It also should be noted that these variations in propellants and J-2S operating characteristics will have an impact on the total mission propulsion operating characteristics. These are diagrammed in Table 2-7 and related to the initial hydrogen condition at launch, i.e., saturated, triple-point, or slush hydrogen.

2.4 INSULATION SYSTEM

In the Douglas study of the baseline S-IVC vehicle stages extensive thermal and meteoroid protection system tradeoffs were performed to optimize the insulation and meteoroid protection systems and to identify and investigate other significant modifications that would reduce heat transfer into the propellant tanks (Ref. 2-7). The combination of structural and insulation system modifications that were recommended by Douglas from results of these trade-offs were assumed in performing this study. However, the thicknesses of insulation to be used on the propellant tank sidewalls and on the common tank bulkheads were reoptimized in this study as a function of system variables for each initial hydrogen condition of interest. The sidewall insulation thicknesses that resulted were then compared with those specified in the Douglas study to ensure that minimum meteoroid protection requirements were satisfied.

Table 2-5

SUMMARY OF SELECTED PROPULSION SYSTEM REQUIREMENTS AND CHARACTERISTICS

Description of Firing	Stage	Nominal Time of Initiation	Basis	NPSP Rqmts			Min. Total Tank Pressure N/cm^2 (psia)	Initial Hydrogen Condition	Nominal Thrust N (lb)	Nominal I_{sp} m/sec (sec)	Mixture Ratio (O/H by wt)	Hydrogen Flow Rate kg/sec (lb/sec)
				Thrust Mode	Engine N/cm^2 (psia)	Net Total N/cm^2 (psia)						
Combined Ascent/Assembly Orbit Adjustment:	All	Main stage -435 sec	Douglas Report DAC-57997	Idle	4.39 (6.45)	4.92 (8.20)	18.0 (30.0)	All	22,240 (5,000)	2726.3 (278.0)	1.0	4.08 (8.99)
• Orbital insertion, plane change, midcourse, and terminal phasing	S-IVC$_1$ & S-IVC$_2$	Liftoff +6.0 hr		Full				LH_2 sat. at 11.2 N/cm^2 (16.2 psia)	1,023,040 (230,000)	4148.4 (423.0)	5.5	38.0 (83.7)
	S-IVC$_3$								863,802 (194,200)	4195.4 (427.8)	4.784	35.6 (78.5)
• Assembly orbit circularization	All							LH_2 sat. at T.P. & 50% SH_2	687,661 (154,600)	4217.0 (430.0)	4.2	31.3 (69.1)
Propellant Settling for OLV Firings	All	Main stage -28.8 sec		Idle		5.04 (8.40)		All	22,240 (5,000)	2726.3 (278.0)	1.0	4.08 (8.99)
First Orbital Launch Main Stage Firing	S-IVC$_1$	S-IVC$_1$ liftoff +707.0 hr		Full				LH_2 sat. at 11.2 N/cm^2(16.2 psia)	1,023,040 (230,000)	4148.4 (423.0)	5.5	38.0 (83.7)
								T.P. LH_2 & 50% SH_2	733,030 (164,800)	4220.0 (430.3)	4.2	33.4 (73.7)
Second Orbital Launch Main Stage Firing	S-IVC$_2$	S-IVC$_2$ liftoff + 683.0 hr						LH_2 sat. at 11.2 N/cm^2(16.2 psia)	1,023,040 (230,000)	4148.4 (423.0)	5.5	38.0 (83.7)
								T.P. LH_2 & 50% SH_2	733,030 (164,800)	4220.0 (430.3)	4.2	33.4 (73.7)
Third Orbital Launch Main Stage Firing		S-IVC$_2$ liftoff. + 686.0 hr						LH_2 sat. at 11.2 N/cm^2(16.2 psia)	1,023,040 (230,000)	4148.4 (423.0)	5.5	38.0 (83.7)
								T.P. LH_2 & 50% SH_2	733,030 (164,800)	4220.0 (430.3)	4.2	33.4 (73.7)
Four Orbital Launch Main Stage Firing	S-IVC$_3$	S-IVC$_3$ liftoff + 62.0 hr						LH_2 sat. at 11.2 N/cm^2(16.2 psia)	863,802 (194,200)	4195.4 (427.8)	4.784	35.6 (78.5)
								LH_2 sat. at T.P.	733,030 (164,800)	4220.0 (430.3)	4.2	33.4 (73.7)
								50% SH_2	709,456 (159,500)	4218.0 (430.1)	4.2	32.3 (71.3)

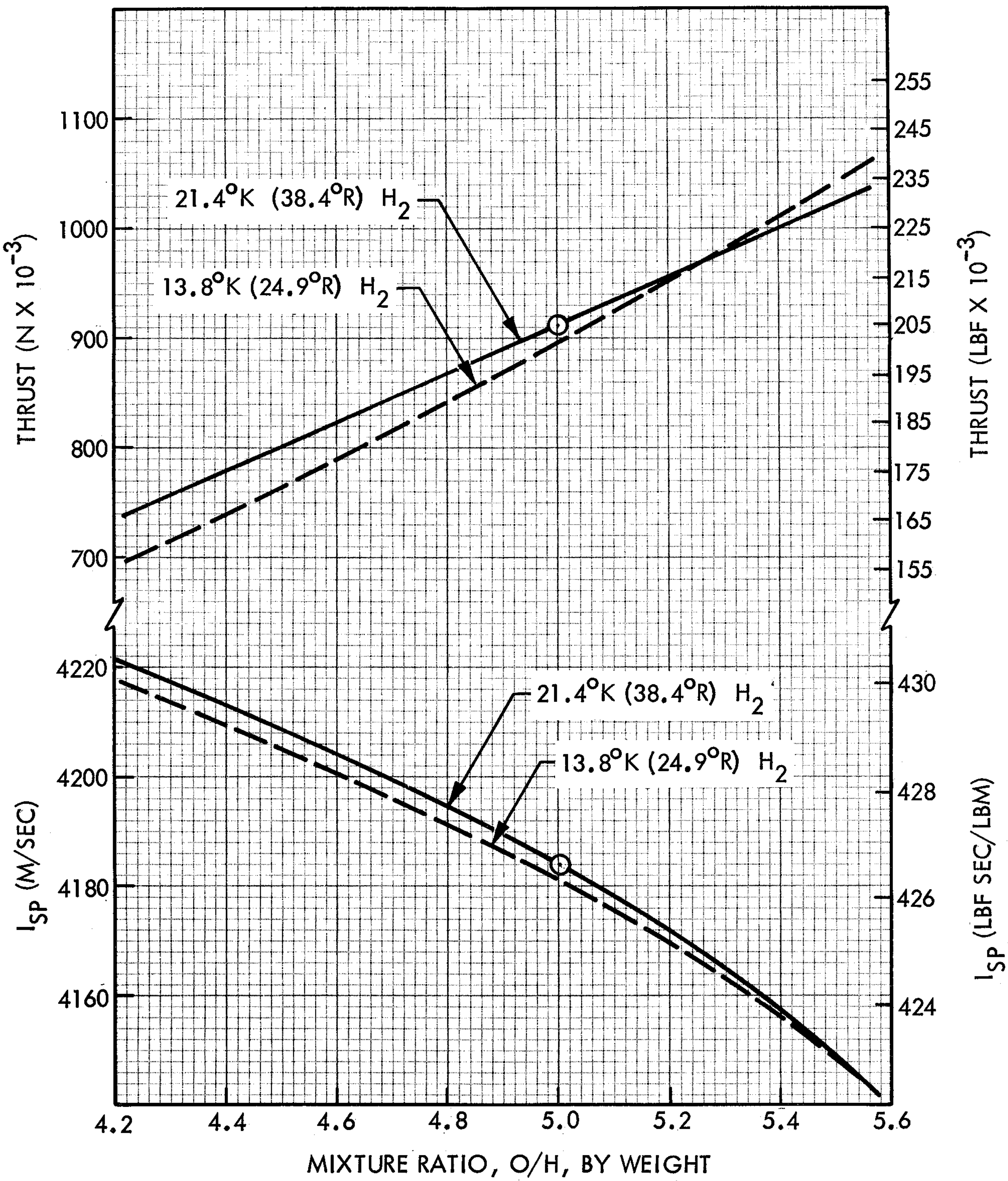

Fig. 2-7 Estimated Thrust and I_{sp} Versus Mixture Ratio for the S-IVC J-2S Engine

Table 2-6

Summary of Transient and Idle-Mode Impulse Propellant Weights

Description of Propellant Usage	Initial Hydrogen Condition											
	LH_2 Sat. at 11.2 N/cm^2 (16.2 psia)				LH_2 Sat. at T. P.				50 Percent Liquid-Solid Mixture			
	O_2 kg (lb)	H_2 kg (lb)	Total kg (lb)	Mixture Ratio	O_2 kg (lb)	H_2 kg (lb)	Total kg (lb)	Mixture Ratio	O_2 kg (lb)	H_2 kg (lb)	Total kg (lb)	Mixture Ratio
S-IV C_1 and S-IV C_3 Stages:												
Idle-Mode Transients	164 (362)	164 (362)	328 (724)	1.0	164 (362)	164 (362)	328 (724)	1.0	164 (362)	164 (362)	328 (724)	1.0
Idle-Mode Impulse for Ascent/Orbit Adjustments	1,656 (3,650)	1,656 (3,650)	3,312 (7,300)	1.0	1,656 (3,650)	1,656 (3,650)	3,312 (7,300)	1.0	1,656 (3,650)	1,656 (3,650)	3,312 (7,300	1.0
Idle-Mode Impulse for Propellant Settling	71 (156)	71 (156)	142 (312)	1.0	71 (156)	71 (156)	142 (312)	1.0	71 (156)	71 (156)	142 (312)	1.0
Mainstage Transients	367 (810)	82 (180)	449 (990)	4.5	367 (810)	82 (180)	449 (990)	4.5	367 (810)	82 (180)	449 (990)	4.5
Total Transient and Idle-Mode Impulse Propellants	2,258 (4,978)	1,973 (4,348)	4,231 (9,326)		2,258 (4,978)	1,973 (4,348)	4,231 (9,326)		2,258 (4,978)	1,973 (4,348)	4,231 (9,326)	
S-IV C_2 Stage:												
Idle-Mode Transients	246 (543)	246 (543)	492 (1,086)	1.0	246 (543)	246 (543)	492 (1,086)	1.0	246 (543)	246 (543)	492 (1,086)	1.0
Idle-Mode Impulse for Ascent/Orbit Adjustments	1,656 (3,650)	1,656 (3,650)	3,312 (7,300)	1.0	1,656 (3,650)	1,656 (3,650)	3,312 (7,300)	1.0	1,656 (3,650)	1,656 (3,650)	3,312 (7,300)	1.0
Idle-Mode Impulse for Propellant Settling	106 (234)	106 (234)	212 (468)	1.0	106 (234)	106 (234)	212 (468)	1.0	106 (234)	106 (234)	212 (468)	1.0
Mainstage Transients	551 (1,215)	122 (270)	673 (1,485)	4.5	551 (1,215)	122 (270)	673 (1,485)	4.5	551 (1,215)	122 (270)	673 (1,485)	4.5
Total Transients and Idle-Mode Impulse Propellants	2,559 (5,642)	2,130 (4,697)	4,689 (10,339)		2,559 (5,642)	2,130 (4,697)	4,689 (10,339)		2,559 (5,642)	2,130 (4,697)	4,689 (10,339)	

Table 2-7

SUMMARY OF PERFORMANCE DATA

Firing Description	Initial Hydrogen Condition	Vehicle Ignition Weight kg (lb)	Engine Thrust Mode	Mission ΔV Increment m/sec (fps)	Engine Mixture Ratio, O/H by wt	Nominal Specific Impulse m/sec (sec)
S-IV C_1, S-IV C_2, and S-IV C_3 Stages:						
Startup Transients	All	A	Idle	0	1.0	–
Impulse for Ascent/Orbit Adjust.	↓	↓	↓	76 (248)	↓	2726 (278.0)
Impulse for Settling Propellants				0		–
Mainstage Transients			Full	0	4.5	–
Impulse for Assembly Orbit Circularization				69 (225)	B	4177 (426.0)
S-IV C_1 Stage:						
Startup Transients	All	–	Idle	0	1.0	–
Impulse for Settling Propellants	↓	–	↓	0	↓	–
Mainstage Transients		–		0		–
Impulse for 1st OLV Firing	LH_2 sat. at 11.2 N/cm^2	391,650 (863,420)	Full	994 (3260)	5.5	4148 (423.0)
↓	LH_2 sat. at T.P.	404,270 (891,240)		1009 (3309)	4.2	4220 (430.3)
	50% liquid-solid mixture	407,470 (898,300)		1013 (3323)	4.2	4220 (430.3)
S-IV C_2 Stage:						
Startup Transients	All	–	Idle	0	1.0	–
Impulse for Settling Propellants	↓	–	↓	0	↓	–
Mainstage Transients		–		0		–
Impulse for 2nd OLV Firing	LH_2 sat. at 11.2 N/cm^2	289,710 (638,700)	Full	303 (995)	5.5	4148 (423.0)
↓	LH_2 sat at T.P.	299,810 (660,960)		312 (1024)	4.2	4220 (430.3)
	50% liquid-solid mixture	301,820 (665,390)		314 (1030)	4.2	4220 (430.3)
Impulse for 3rd OLV Firing	LH_2 sat. at 11.2 N/cm^2	268,810 (592,610)		1074 (3524)	5.5	4148 (423.0)
↓	LH_2 sat. at T.P.	277,980 (612,820)		1106 (3630)	4.2	4220 (430.3)
	50% liquid-solid mixture	279,660 (616,530)		1118 (3667)	4.2	4220 (430.3)
S-IV C_3 Stage:						
Startup Transients	All	–	Idle	0	1.0	–
Impulse for Settling Propellants	↓	–	↓	0	↓	–
Mainstage Transients		–		0		–
Impulse for 4th OLV Firing	LH_2 sat. at 11.2 N/cm^2	189,100 (416,890)	Full	2708 (8884)	4.784	4195 (427.8)
↓	LH_2 sat. at T.P.	195,490 (430,980)		2652 (8700)	4.2	4220 (430.3)
	50% liquid-solid mixture	196,210 (432,560)		2634 (8643)	4.2	4218 (430.1)

NOTES:

[A] Ignition weight = 121,110 kg (267,000 lb) for all cases, except S-IV C_2 ignition weight when fueled with LH_2 initially sat. at 11.2 N/cm^2 (16.2 psia).

[B] Engine mixture ratio = 5.5 for S-IV C_1 and S-IV C_2 when fueled with LH_2 initially sat. at 11.2 N/cm^2 (16.2 psia); S-IV C_3 mixture ratio when fueled with LH_2 initially sat. at 11.2 N/cm^2 (16.2 psia); and mixture ratio = 4.2 for all other cases.

The basic thermal/meteoroid protection system that was selected consists of the following: (1) a fiberglass heat block that structurally attaches the forward skirt to the tank sidewall, (2) a high-performance insulation blanket mounted external to the LH_2 tank forward dome (with existing internal insulation removed), (3) combination high-performance insulation blankets and meteoroid bumpers mounted external to the LH_2 tank sidewall and aft skirt (with existing internal insulation removed), (4) a fiberglass heatblock that structurally attaches the two segments of the aft dome at the circumferential ring where they are intersected by the common bulkhead, (5) polyurethane foam insulation mounted on the hydrogen side of the common tank bulkhead, (6) aluminum silicone paint on the LH_2 tank aft dome and thrust structure, and (7) a fiberglass shroud mounted external to the aft docking structure to shield the LO_2 tank from direct solar radiation.

The forward fiberglass heat block is a 22.9-cm (9-in.) long, 1.111-cm (0.4375-in.) thick fiberglass honeycomb sandwich cylinder with aluminum closing angles that thermally isolates the tank sidewall from the forward skirt. The common bulkhead heat block is a 0.660-cm (0.26-in.) thick fiberglass splice strap that joins the existing common bulkhead attachment angles after the connecting material has been machined away during rework.

The high-performance insulation blanket mounted to the external surface of the forward dome consists of 50 layers of aluminized Mylar (NRC-2).

The combination high-performance insulation blankets and meteoroid protection bumpers mounted to the external surface of the LH_2 tank sidewall and aft skirt are made from the Goodyear Aerospace High-Performance Insulation System (Ref. 2-8). Two concentric blankets were used on the S-IVC$_1$, and S-IVC$_2$ stages, while only a single blanket (of the same configuration as the outer S-IVC$_1$/S-IVC$_2$ stage blankets) was used on the S-IVC$_3$ stage. The outer blanket is 8.96 m. (29.4 ft) long, with a 0.56-cm (0.22-in.) thick fiberglass bumper and a thermal protection system composed of alternate layers of 0.00635 mm (0.25 mil) aluminized Mylar and 0.089-cm (0.035-in.) thick polyurethane foam spacers. The inner blanket is 6.78 m (22.25 feet) in length and consists of alternate layers of the aluminized Mylar and foam as described for the outer blanket. Each blanket is made up of six 3.51-m (11.5-ft) wide panels. These panels are supported at both ends by an edge attachment to the forward and aft skirt sidewall flanges.

The polyurethane foam used on the hydrogen side of the common tank bulkhead is 80.1 kg/m^3 (5 lb/ft^3) density foam similar to that presently installed on the S-IVB tank sidewall and forward dome.

The insulation system thicknesses for the three S-IVC stages were optimized in this study by calculation of heat transferred through each segment of the hydrogen tanks, resulting hydrogen boiloff weights, and system component weights, and by then comparing the total effective boiloff and insulation weights for several discrete thicknesses of bulkhead and sidewall insulation.

2.4.1 Heat Transferred to the Hydrogen

To determine heat transfer rates and total heat quantities absorbed by the hydrogen tanks of the three S-IVC stages, the Earth launch mission profile for each stage was separated into three time periods. These were (1) prelaunch hold, (2) ascent and cooldown, and (3) Earth orbit. Environmental heating is significantly different during each of these periods. Total heat transferred into the hydrogen tank during each period for each stage was determined by summing that transferred through the following: (1) the forward dome and joint, (2) the cylindrical sidewall, (3) the aft skirt and joint, (4) the common tank bulkhead, (5) plumbing penetrations, (6) helium pressurant bottle supports, and (7) pressurization gases. Values of thermal conductivity, temperature differentials, and penetration heat leaks used in the analysis were either taken from the details of the Douglas study or calculated.

For purposes of this analysis, prepressurization of the hydrogen tank was assumed to occur when topping or recirculation of the propellant was terminated for a 180-sec prelaunch hold period. Also, the tank sidewall cooldown period from launch through high ascent heating to steadystate orbit heating was assumed to be 6 hr, although the actual time would be dependent on insulation thickness, purge gas outgassing, and other factors. The assumed steadystate orbit heating period was then varied in the analysis for each of the three S-IVC stages as shown in Fig. 2-5.

Total accumulated heat quantities absorbed by the hydrogen were calculated from the transient heating histories using the assumptions described above. Results are presented in Figs. 2-8 through 2-13 for each of the three stages fueled with hydrogen at each of the three initial conditions of interest. These figures show that total heat transfer to the hydrogen increases by approximately 1.5 percent for triplepoint liquid, and by approximately 4.0 percent for 50-percent slush, over that corresponding to liquid initially saturated at 11.2 N/cm^2 (16.2 psia) for the S-IVC$_1$, and S-IVC$_2$ stages where identical optimum insulation thicknesses resulted for all initial hydrogen conditions. It can further be seen that the total heat transfer increases for triple-point liquid and 50-percent slush over that corresponding to saturated liquid by approximately 30 and 33 percent, respectively, for the S-IVC$_3$ stage where the insulation thicknesses optimized differently for saturated and subcooled hydrogen.

Heat absorption from pressurant gases for each of the three S-IVC stages was found in the analysis to vary with the initial propellant condition depending on the quantity of pressurant required and the type of pressurant gas being used for each particular pressurization or expulsion cycle. A summary of the heat transfer from pressurant gases into the hydrogen is presented in Table 2-8. The values presented are included in the total heat absorption time histories of Figs. 2-8 through 2-13.

2.4.2 Insulation Thickness Optimizations

The procedure used to optimize the insulation thicknesses for each of the S-IVC stages was similar to that used in the initial contract study for the S-IVB/LASS vehicle (Ref. 2-9). A simplified model was used to predict boiloff hydrogen weights for this purpose. The model assumed complete thermodynamic mixing of the hydrogen

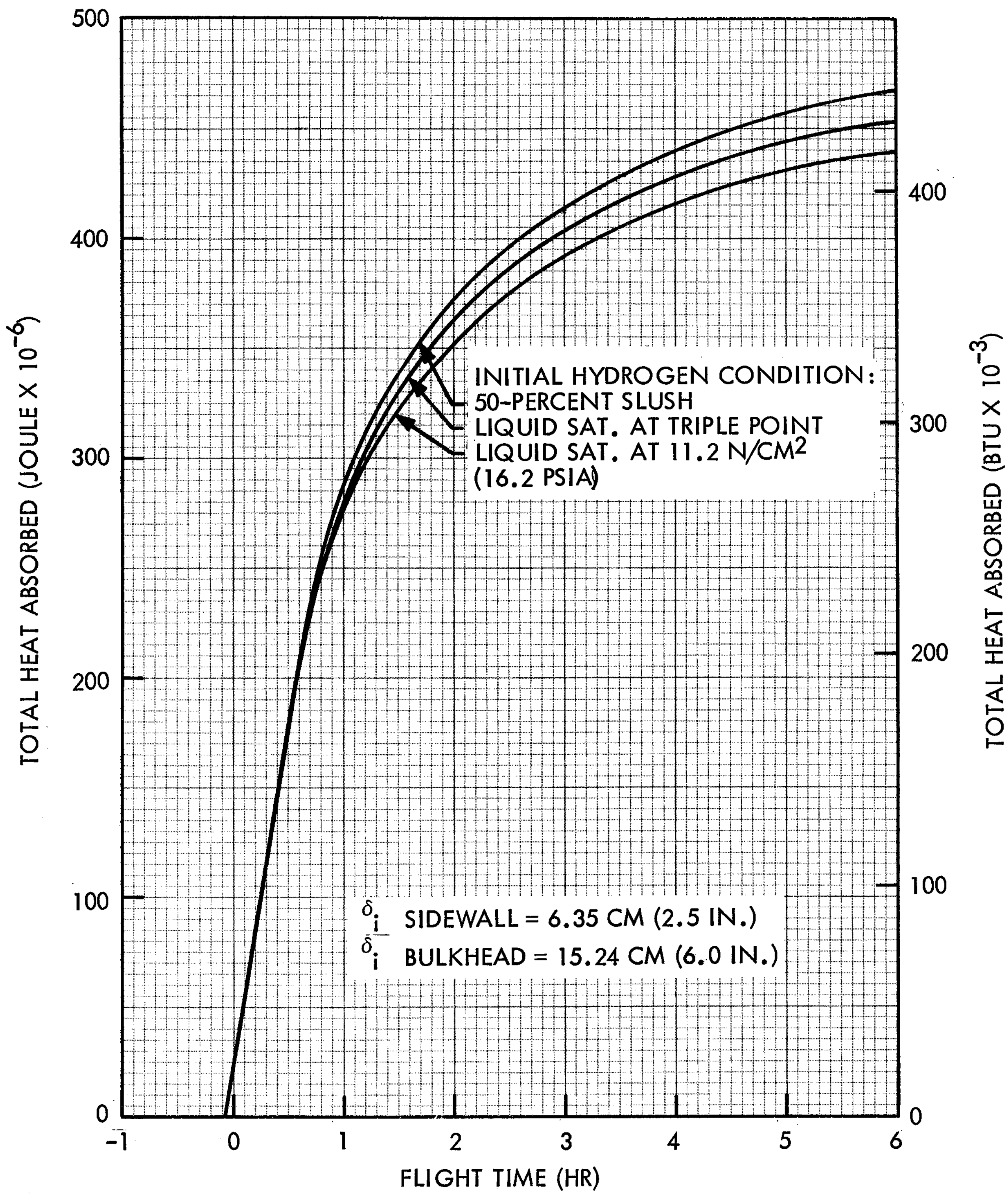

Fig. 2-8 Predicted Heat Transfer to the Hydrogen Tank During Ascent for the S-IVC$_1$ Stage

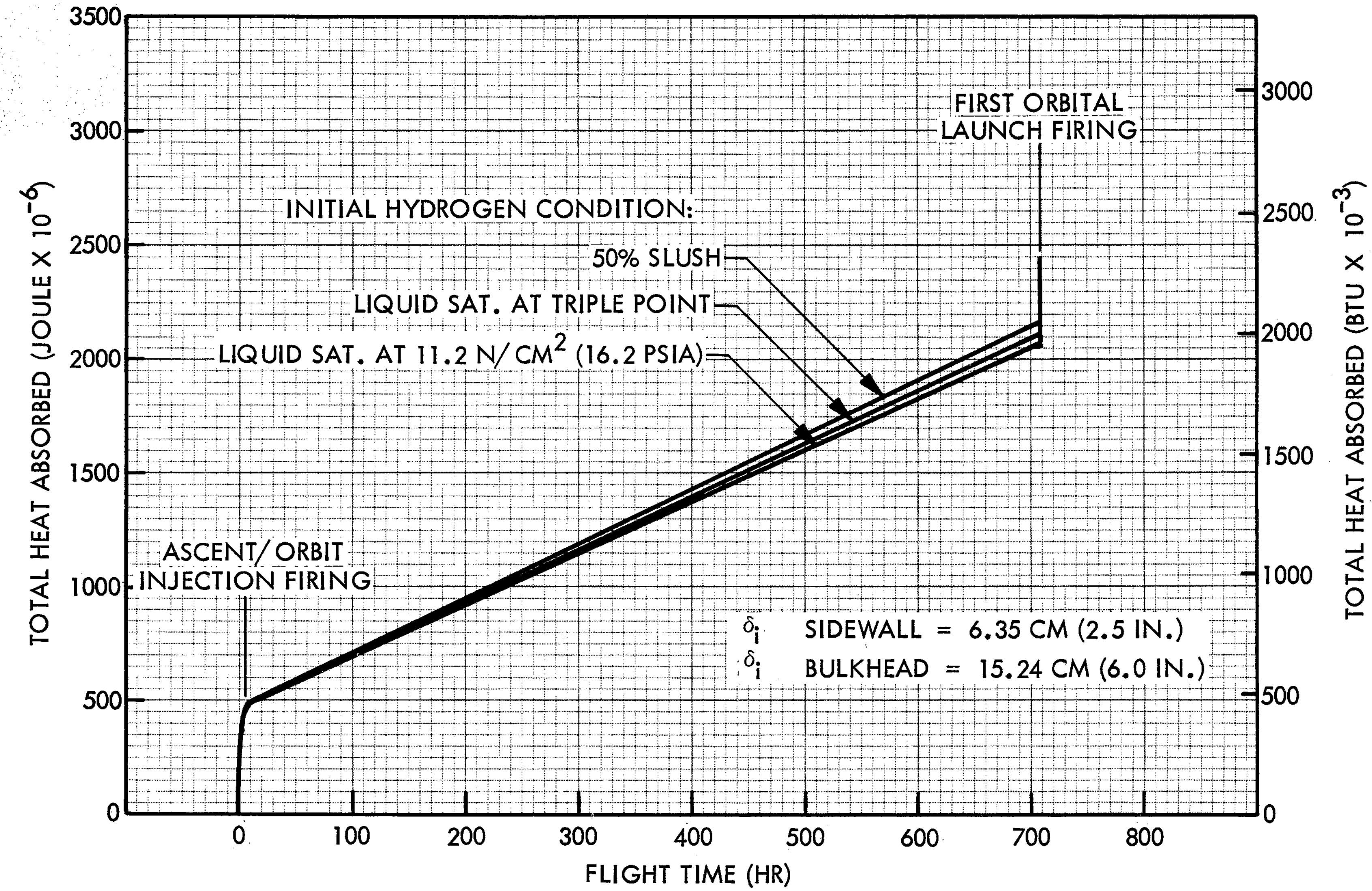

Fig. 2-9 Predicted Heat Transfer to the Hydrogen Tank During Orbital Storage for the S-IVC$_1$ Stage

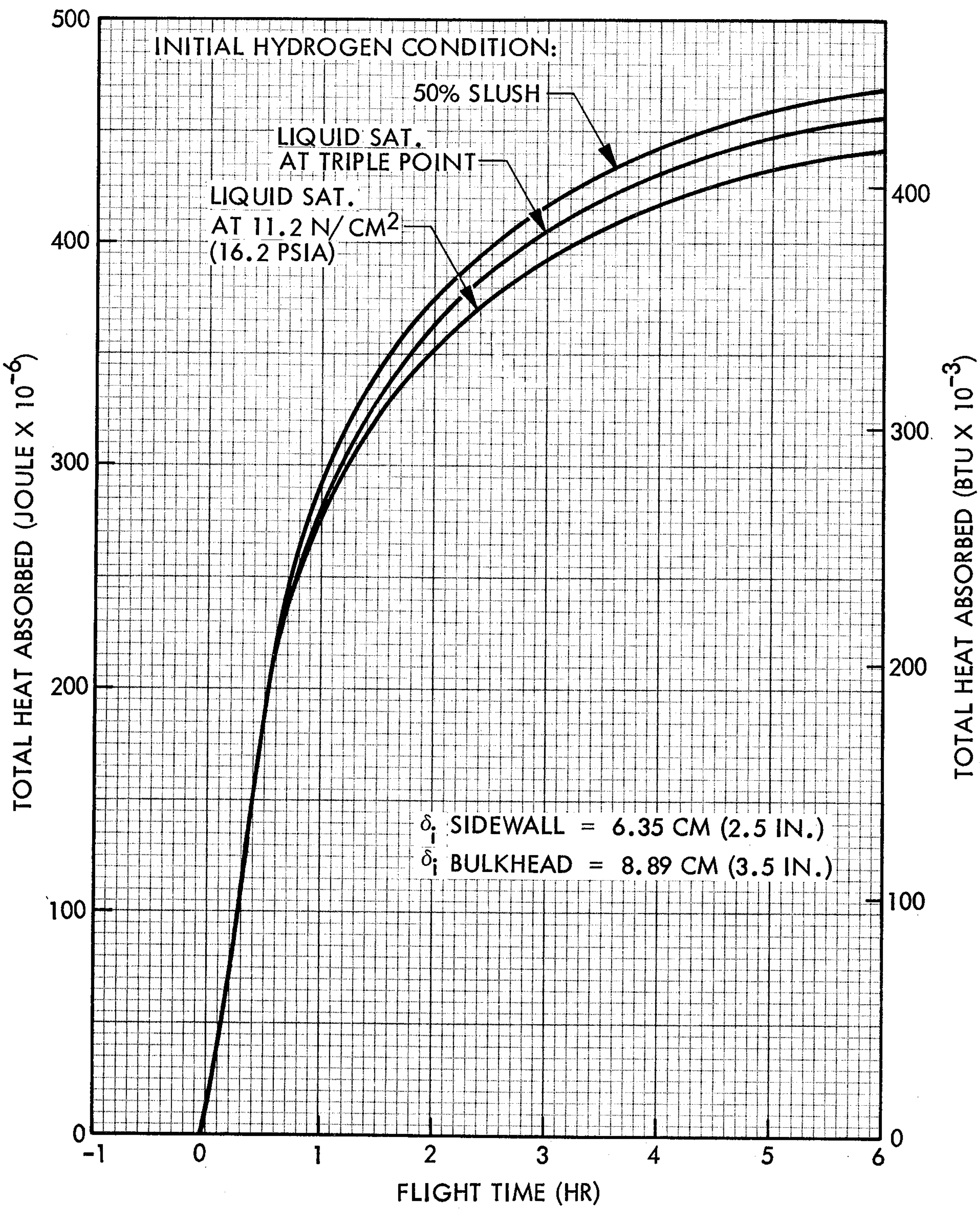

Fig. 2-10 Predicted Heat Transfer to the Hydrogen Tank During Ascent for the S-IVC$_2$ Stage

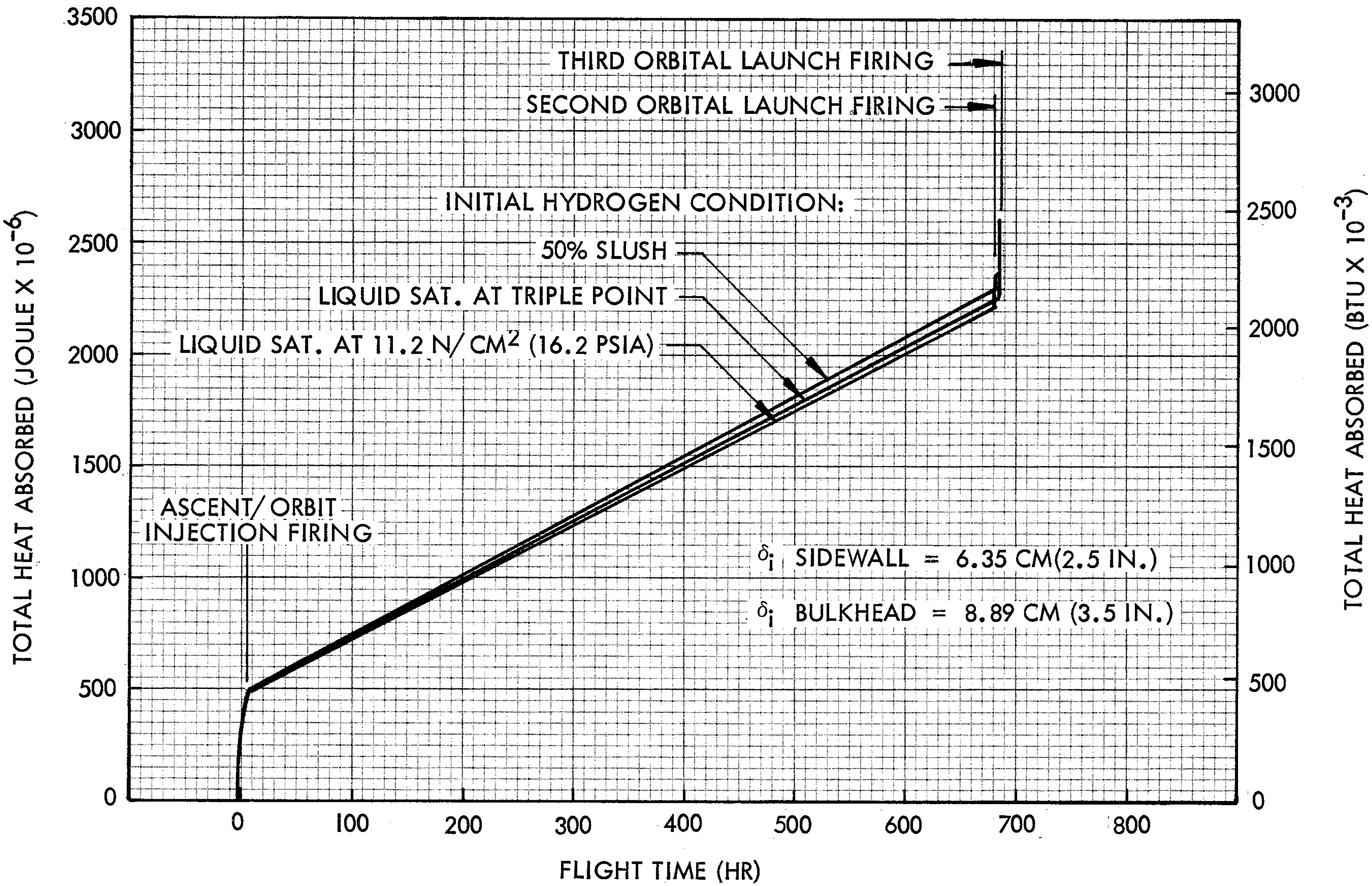

Fig. 2-11 Predicted Heat Transfer to the Hydrogen Tank During Orbital Storage for the S-IVC_2 Stage

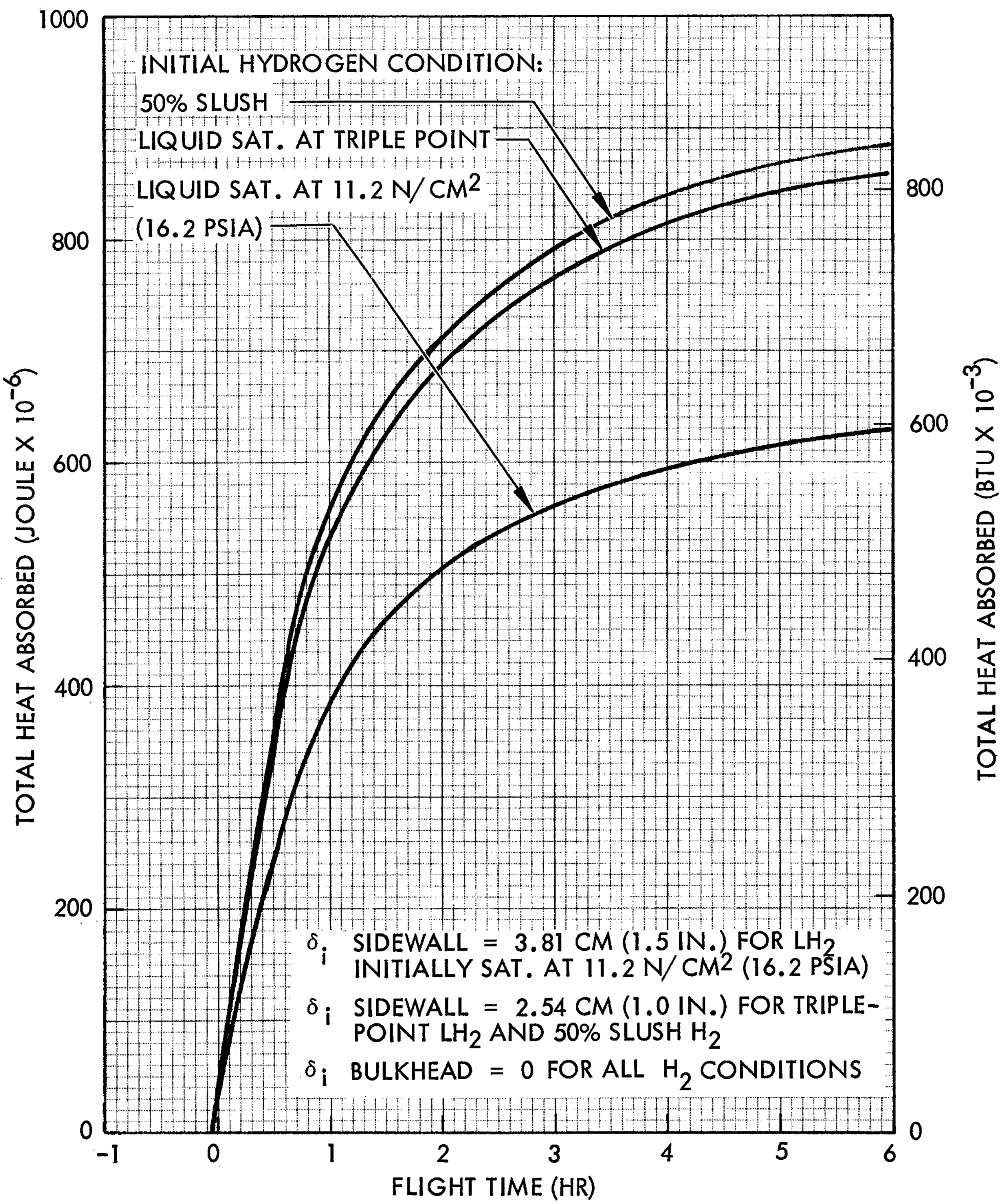

Fig. 2-12 Predicted Heat Transfer to the Hydrogen Tank During Ascent for the S-IVC$_3$ Stage

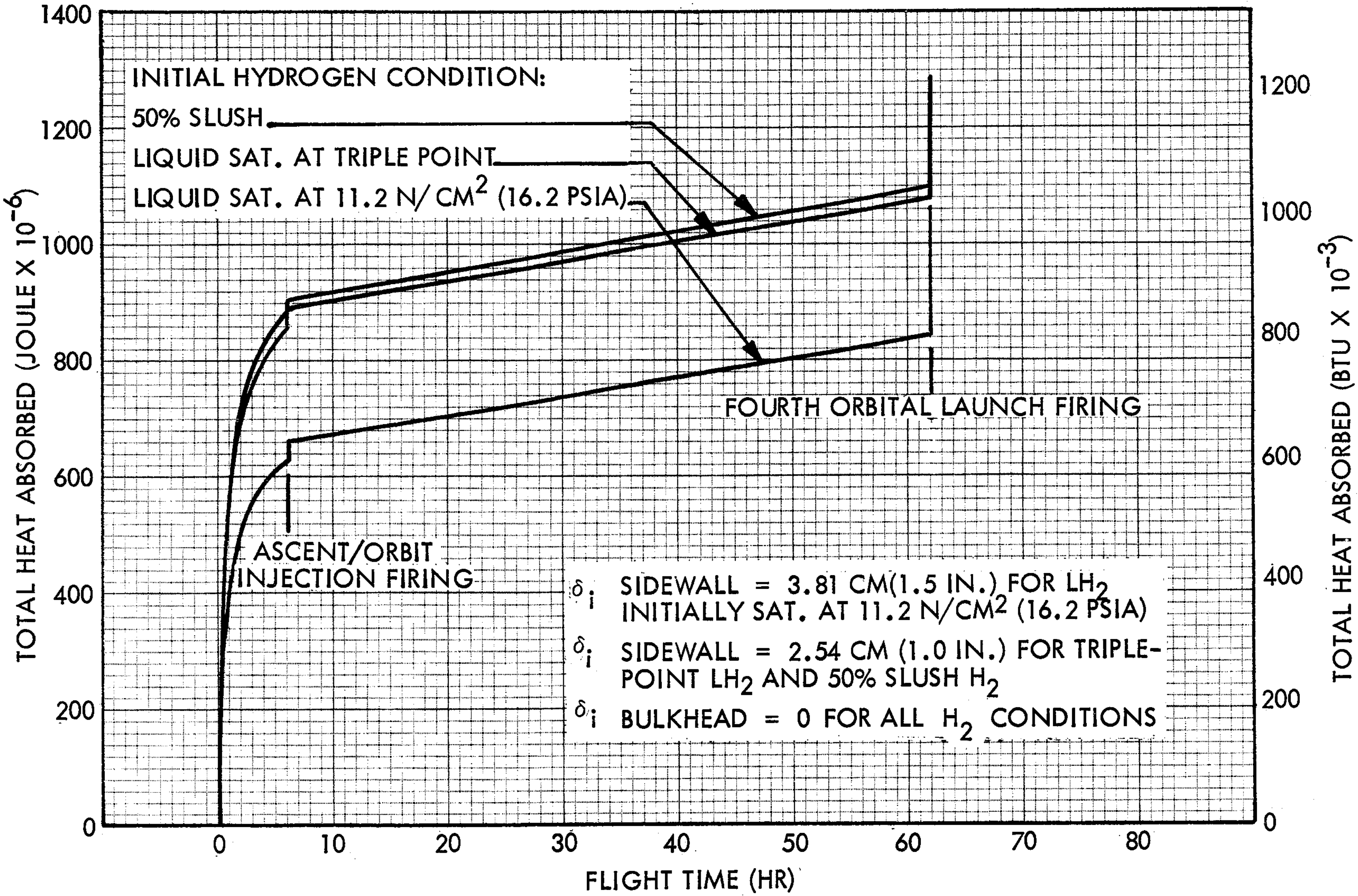

Fig. 2-13 Predicted Heat Transfer to the Hydrogen Tank During Orbital Storage for the S-IVC$_3$ Stage

Table 2-8
SUMMARY OF HEAT TRANSFERRED TO THE HYDROGEN FROM PRESSURANTS

Pressurization Function	Initial Hydrogen Condition								
	LH_2 Sat. at 11.2 N/cm^2 (16.2 psia)			LH_2 Sat. at T. P.			50 Percent Liquid-Solid Mixture		
	Pressurant Wt kg (lb)	Hardware Wt kg (lb)	Mode	Pressurant Wt kg (lb)	Hardware Wt kg (lb)	Mode	Pressurant Wt kg (lb)	Hardware Wt kg (lb)	Mode
S-IV C_1 Stage:									
Prepressurization	2.7 (5.9)	0	A	51.3 (113.1)	0	B	197.2 (434.8)	0	B
Expulsion for Ascent Firing	25.4 (56.1)	0	D	19.3 (42.6)	0	D	18.6 (40.9)	0	D
Repressurization	22.1 (48.8)	33.2 (73.2)	C	7.8 (17.2)	11.7 (25.8)	C	4.9 (10.9)	7.4 (16.4)	C
Expulsion for 1st OLV Firing	143.5 (316.4)	0	D	186.4 (411.0)	0	D	223.8 (493.4)	0	D
Totals GHe	24.8 (54.7)			59.1 (130.3)			202.1 (445.7)		
Totals GH_2	168.9 (372.5)			205.7 (453.6)			242.4 (534.3)		
Totals Hardware		33.2 (73.2)			11.7 (25.8)			7.4 (16.4)	
S-IV C_2 Stage:									
Prepressurization	4.5 (10.0)	0	A	51.8 (114.1)	0	B	187.9 (414.3)	0	B
Expulsion for Ascent Firing	25.4 (55.9)	0	D	19.3 (42.6)	0	D	18.6 (40.9)	0	D
Repressurization	23.3 (51.4)	35.0 (77.1)	C	8.4 (18.6)	12.6 (27.9)	C	5.7 (12.5)	8.6 (18.8)	C
Expulsion for 2nd OLV Firing	35.5 (78.3)	0	D	46.7 (102.9)	0	D	48.6 (107.2)	0	D
Repressurization	30.8 (67.9)	46.2 (101.9)	C	21.9 (48.3)	32.9 (72.5)	C	20.9 (46.0)	31.4 (69.0)	C
Expulsion for 3rd OLV Firing	108.5 (239.1)	0	D	141.5 (312.0)	0	D	146.4 (322.8)	0	D
Totals GHe	58.6 (129.3)			82.1 (181.0)			214.5 (472.8)		
Totals GH_2	169.4 (373.3)			207.5 (457.5)			213.6 (470.9)		
Totals Hardware		81.2 (179.0)			45.5 (100.4)			40.0 (87.8)	
S-IV C_3 Stage:									
Prepressurization	2.6 (5.8)		C	109.2 (240.8)	0	B	164.7 (363.2)	0	B
Expulsion for Ascent Firing	27.0 (59.5)	0	D	25.8 (56.9)	0	D	19.1 (42.1)	0	D
Repressurization	13.9 (30.7)	20.9 (46.1)	C	6.8 (15.1)	10.2 (22.7)	C	13.7 (30.2)	20.6 (45.3)	C
Expulsion for 4th OLV Firing	173.0 (381.5)	0	D	170.1 (375.0)	0	D	163.3 (359.9)	0	D
Totals GHe	16.5 (36.5)			116.0 (255.9)			178.4 (393.4)		
Totals GH_2	200.0 (441.0)			195.9 (431.9)			182.4 (402.0)		
Totals Hardware		20.9 (46.1)			10.2 (22.7)			20.6 (45.3)	

Modes of Pressurization:

A Ground facility helium at 20.7°K (37.2°R).
B Ground facility helium at 13.8°K (24.9°R).
C Helium stored in spherical bottles at LH_2 temp., heated to 138.9°K (250°R) with gas burner, M/M_{reqd} = 2.5.
D GH_2 engine bleed at 111°K (200°R).

throughout the mission. All heat absorbed by the system after prepressurization on the launch pad was assumed to raise the initial energy level of the hydrogen until saturated conditions at the engine start pressure required for the orbital launch firing were reached. After initial saturation at this pressure of $17.24 N/cm^2$ (25 psia), all subsequent heat absorbed was assumed to result in boiloff of the liquid. An average heat of vaporization value was used which corresponds to the average of the initial and final cyclic vent pressures of $26.89 N/cm^2$ (39psia) and $10.34 N/cm^2$ (15 psia), respectively.

Calculated boiloff hydrogen weights were multiplied by mission tradeoff factors (boiloff factors) derived to determine the total effective vehicle payload weight penalties that corresponded to the actual boiloff weights for each of the three S-IVC stages. Similar tradeoff factors were derived and multiplied by insulation inert weights to determine their effect on total vehicle payload weight. The payload partials that were derived are as follows:

Stage	$S\text{-}IVC_1$	$S\text{-}IVC_2$	$S\text{-}IVC_3$
$\frac{\partial W_{PL}}{\partial W_{BO}}$	- 0.3178	-0.3178	-0.3178
$\frac{\partial W_{PL}}{\partial W_{INERT}}$	-0.4137	-0.5701	-1.0

These tradeoff factors were derived assuming that all boiloff in all three stages occurred before the first orbital launch vehicle ignition, and further that tank inert weights were not varied to accommodate changes in propellant load due to boiloff.

Total OLV payload penalties were calculated by simply summing the effective boiloff and insulation inert weight penalties discussed above. These totals were then plotted as a function of sidewall and common tank bulkhead insulation thicknesses. Results of the optimizations are presented in Figs. 2-14 through 2-19.

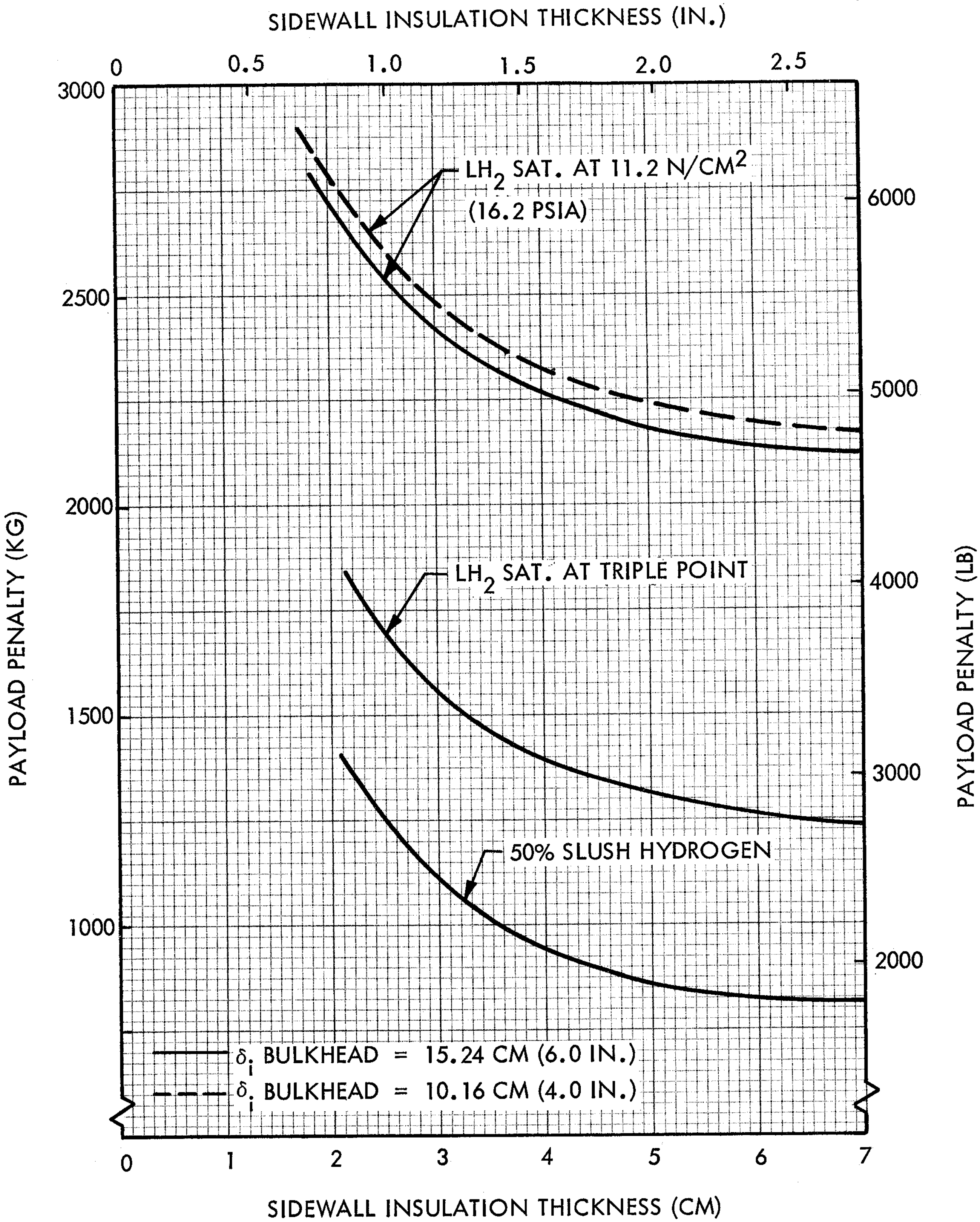

Fig. 2-14 Payload Weight Penalty As a Function of Sidewall Insulation Thickness for the S-IVC$_1$ Stage

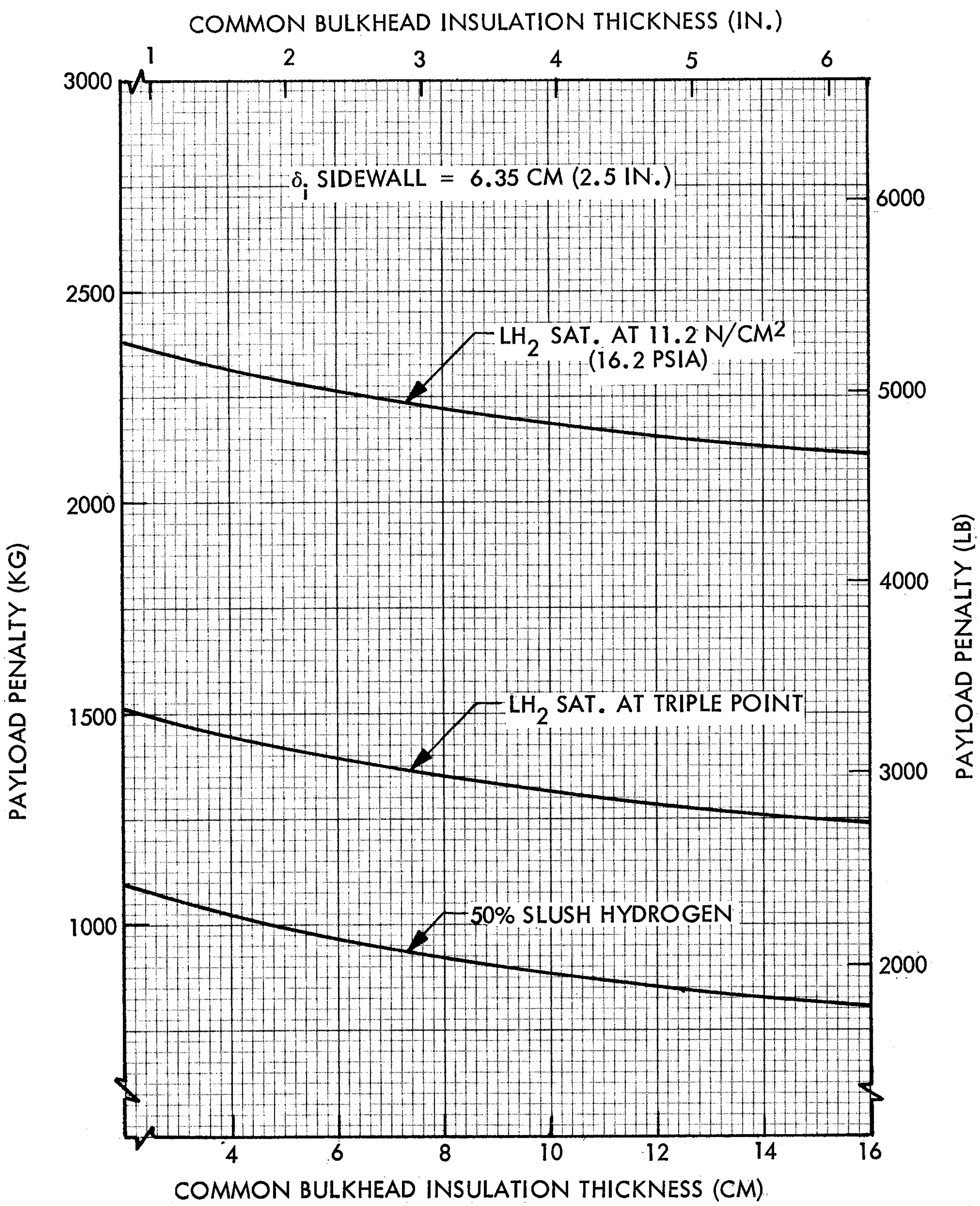

Fig. 2-15 Payload Weight Penalty As a Function of Common Bulkhead Insulation Thickness for the S-IVC$_1$ Stage

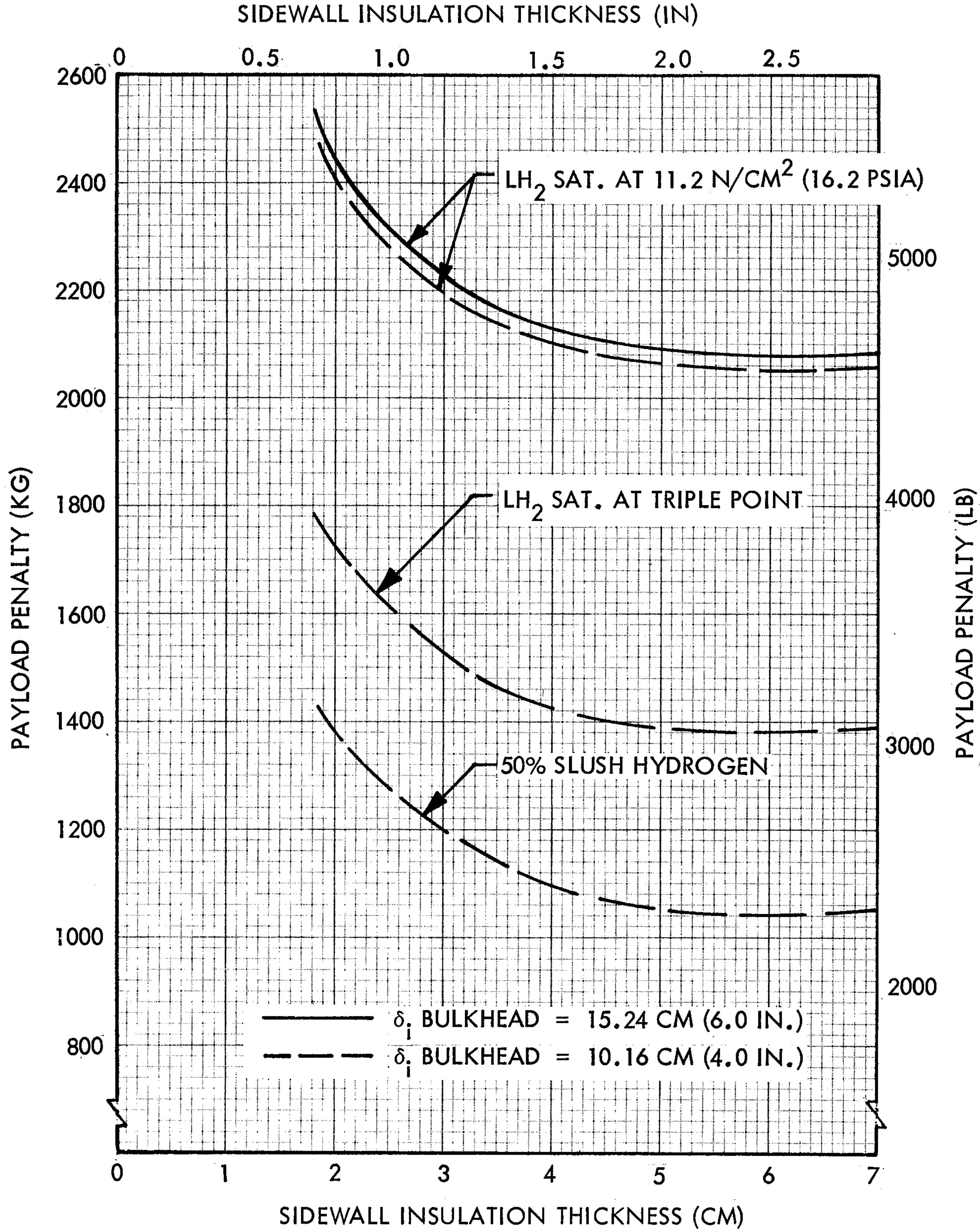

Fig. 2-16 Payload Weight Penalty As a Function of Sidewall Insulation Thickness for the S-IVC$_2$ Stage

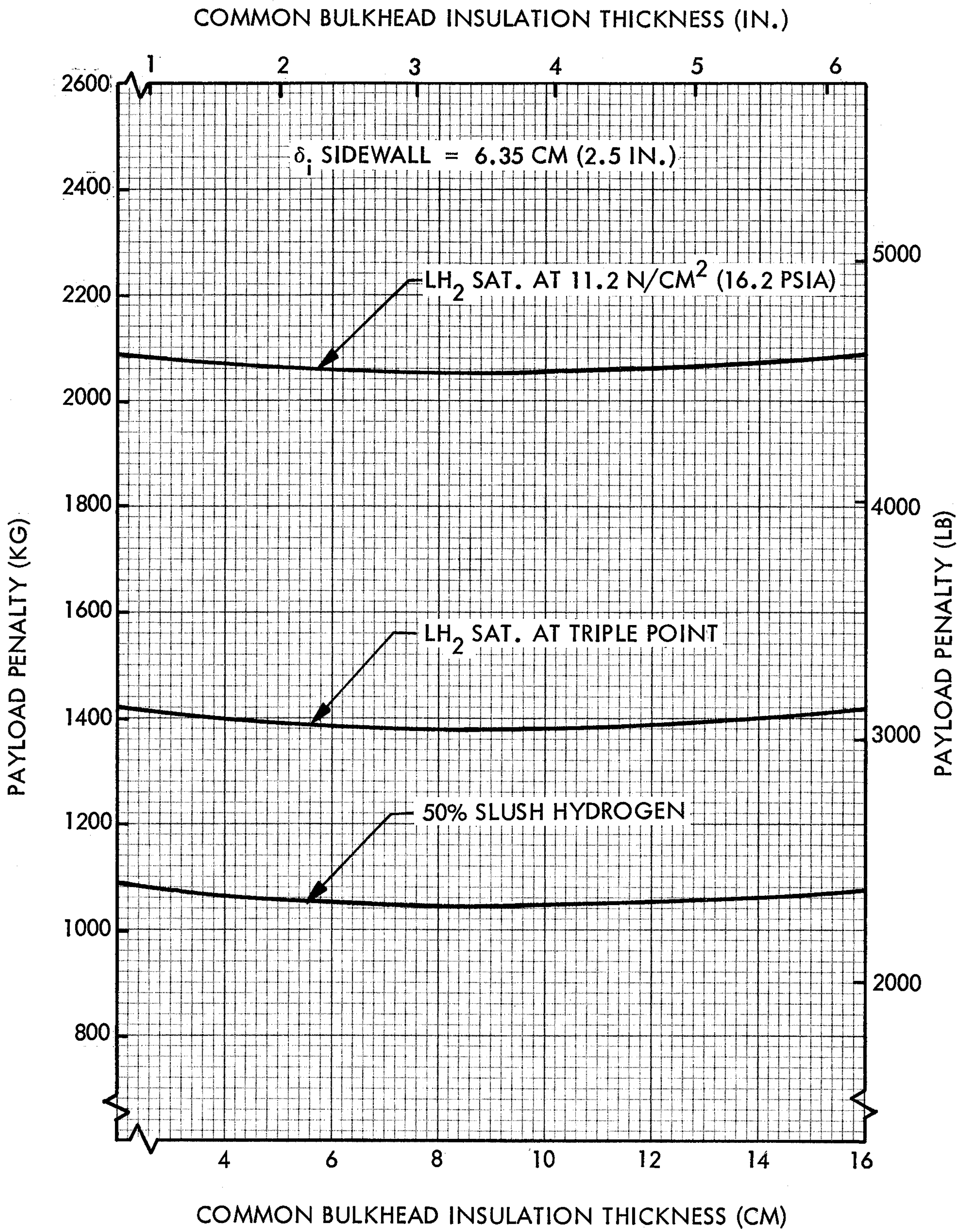

Fig. 2-17 Payload Weight Penalty As a Function of Common Bulkhead Insulation Thickness for the S-IVC$_2$ Stage

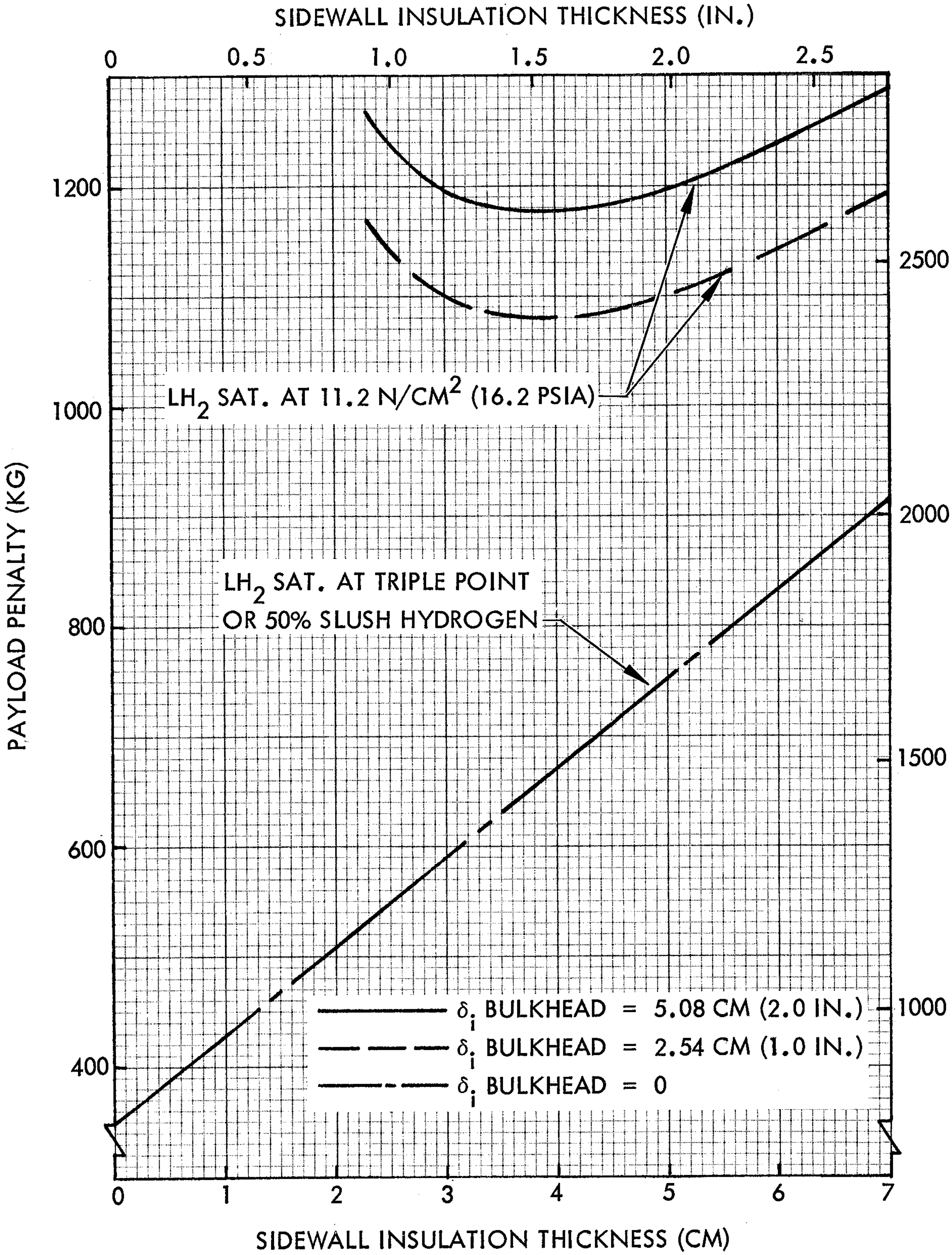

Fig. 2-18 Payload Weight Penalty As a Function of Sidewall Insulation Thickness for the S-IVC$_3$ Stage

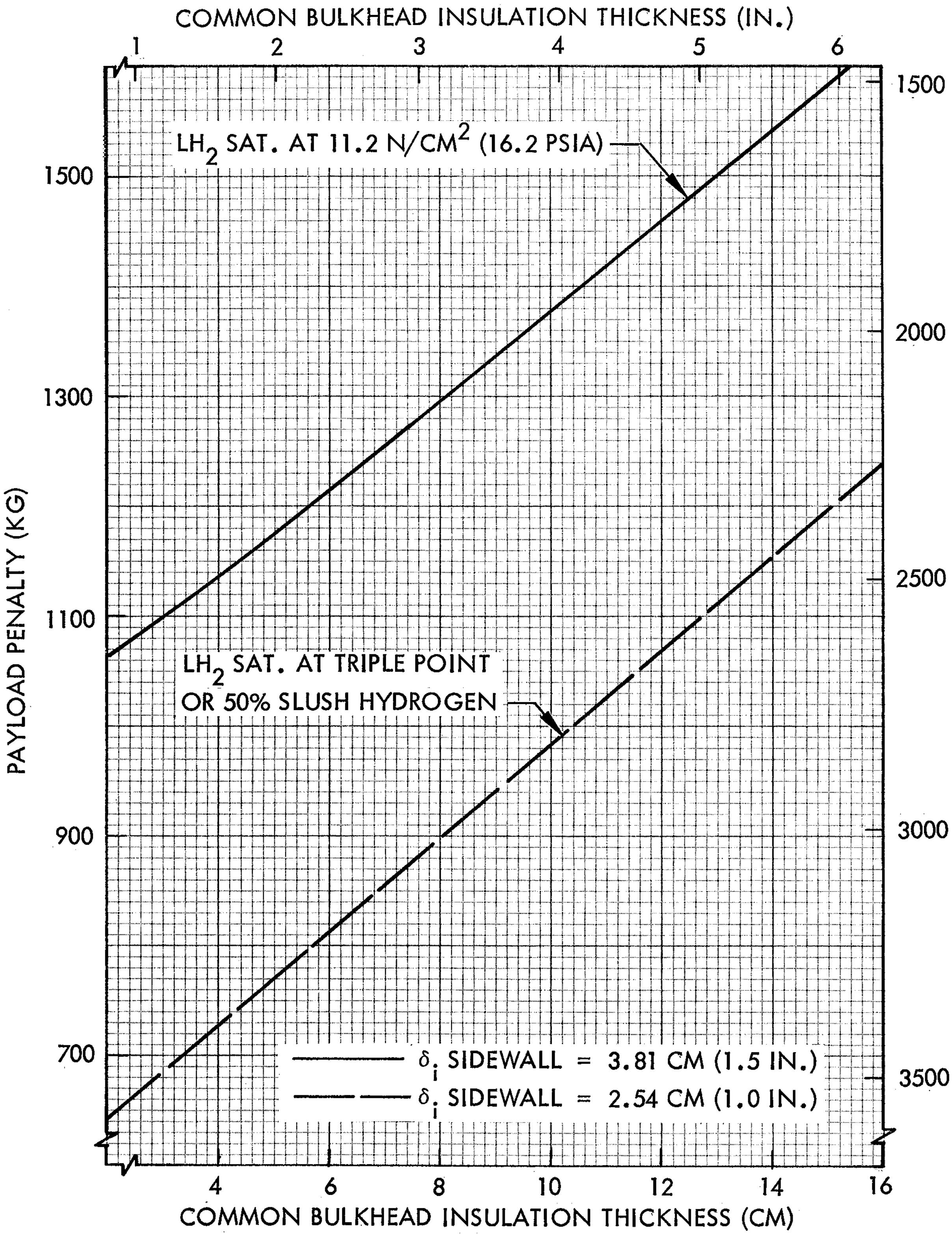

Fig. 2-19 Payload Weight Penalty As a Function of Common Bulkhead Insulation Thickness for the S-IVC$_3$ Stage

It can be seen by inspection of Figs. 2-14 through 2-17 that the optimum sidewall insulation thickness for the S-IVC$_1$ and S-IVC$_2$ stages is approximately 6.35 cm (2.5 in.) for each of the three initial hydrogen conditions of interest. Also, it can be seen that the true optimum common bulkhead insulation thickness is greater for the S-IVC$_1$ stage than for the S-IVC$_2$ stage for all initial hydrogen conditions but that the effect of off-optimum thickness is small. It was for this reason that a common thickness of 15.24 cm (6 in.) was selected for stage commonality. (this thickness was also selected in the Douglas study).

The data presented in Fig. 2-18 show that the optimum sidewall insulation thickness for the S-IVC$_3$ stage fueled with 50-percent slush hydrogen would be zero based on the effective payload penalty. However, this is not practical considering groundhold insulation requirements, and it also would not satisfy minimum meteoroid protection requirements. Therefore, the thickness of 2.54 cm (1.0 in.), calculated to be the minimum that would satisfy meteoroid protection requirements, was selected. Data presented in Fig. 2-19, however, show that the optimum common tank bulkhead insulation thickness for the S-IVC$_3$ stage for all initial hydrogen conditions is zero, and this value was then used in subsequent analysis.

2.5 VENTING SYSTEM

The cyclic venting mode specified by Douglas in the baseline S-IVC vehicle study (Ref. 2-10) was used to develop the venting analysis for this study. In brief, the model provides that hydrogen tank venting will be accomplished in cycles, since the total quantity of hydrogen vented during the orbital storage period would not be sufficient to provide sustained venting using the existing S-IVB/V continuous vent system at a high enough thrust level to prevent liquid entrainment and loss in the vent gases. Any LO_2 tank venting that is required would be accomplished during the hydrogen vent cycles while the propellants are settled in the respective tanks. In this mode, the impulse to settle initially the propellants for any particular vent cycle would be provided by a short firing of the auxiliary propulsion system (APS) motors. When an acceleration level of 10^{-4} g's is reached, the hydrogen tank vent valve will be opened, the APS firing will be terminated, and the thrust of the vent gases directed through an aft-facing propulsive vent nozzle system to provide sufficient acceleration to keep the propellants settled during the remainder of the cycle.

To minimize the number of vent cycles required, the upper and lower hydrogen tank pressures for each vent cycle were set as far apart as possible at 26.89 N/cm^2 (39 psia) and 10.34 N/cm^2 (15 psia), respectively. This upper pressure is limited by the structural capability of the S-IVC hydrogen tanks, while the lower limit is the minimum pressure that will provide sufficient thrust during venting to ensure that no liquid entrainment occurs (corresponding to well above the "safe" minimum of 5×10^{-5} g's established by the S-IVB AS-203 flight).

The analytical model used in this study to determine hydrogen tank pressure-time histories and quantities of vented hydrogen for the three S-IVC stages was that developed for this specific purpose in the initial Lockheed contract study (Ref. 2-11). This model also assumes complete thermal mixing of the hydrogen to control tank pressure*. All heat transferred into the hydrogen after initial saturation is distributed to both the liquid and the vapor in evaluating energy balances during the alternate storage and vent cycles.

In performing the venting analysis for this study, hydrogen quantities in the tank during venting as well as other factors affecting venting were determined by first performing a preliminary, and subsequently a final, venting analysis based on results of an intermediate preliminary performance analysis. The hydrogen tank pressure-time histories that resulted from the final venting analysis are presented in Figs. 2-20 through 2-28, and a summary of vent characteristics is given in Table 2-9.

The tank pressure-time histories show that variation of the predicted venting times caused by uncertainties in hydrogen quantities, temperatures, and heat absorption by

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*Mixing studies performed during the 41.5-in.-diam. tank test program indicate this concept is valid, but additional test demonstration is needed.

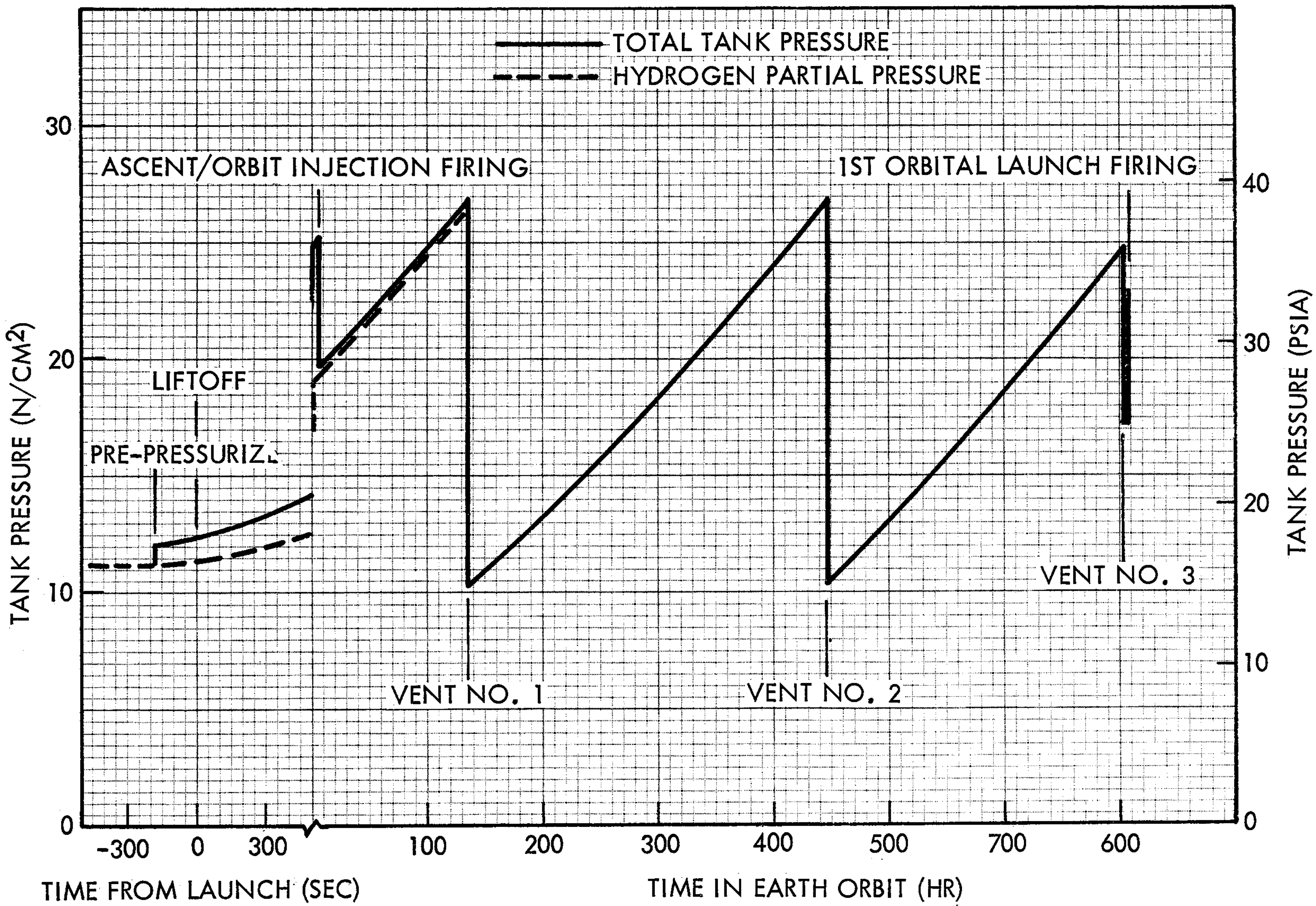

Fig. 2-20 Hydrogen Tank Pressure-Time History for S-IVC$_1$ Stage Fueled With LH$_2$ Initially Saturated at 11.2 N/cm^2 (16.2 psia)

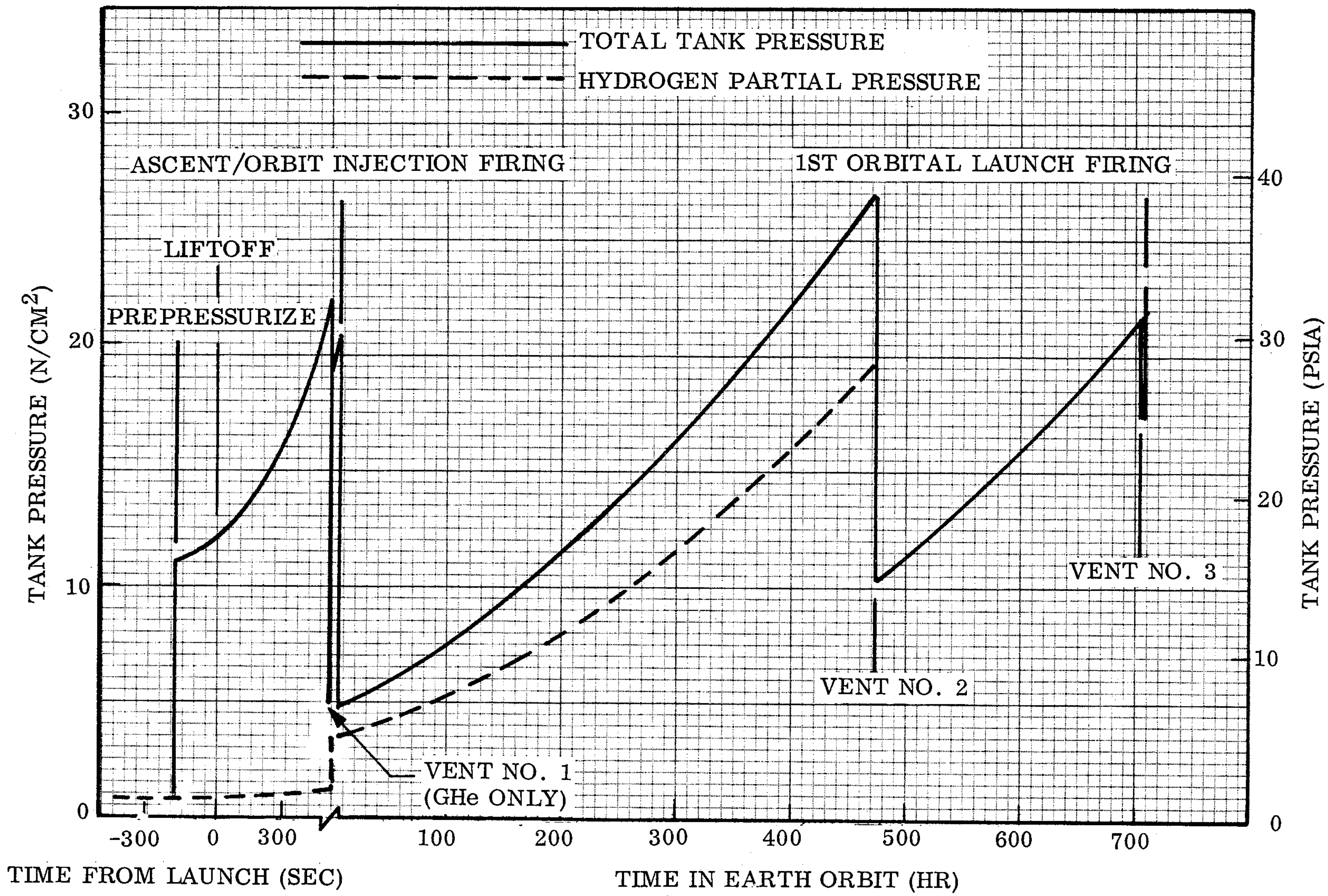

Fig. 2-21 Hydrogen Tank Pressure-Line History for S-IVC$_1$ Stage Fueled with LH_2 Initially Saturated at the Triple Point

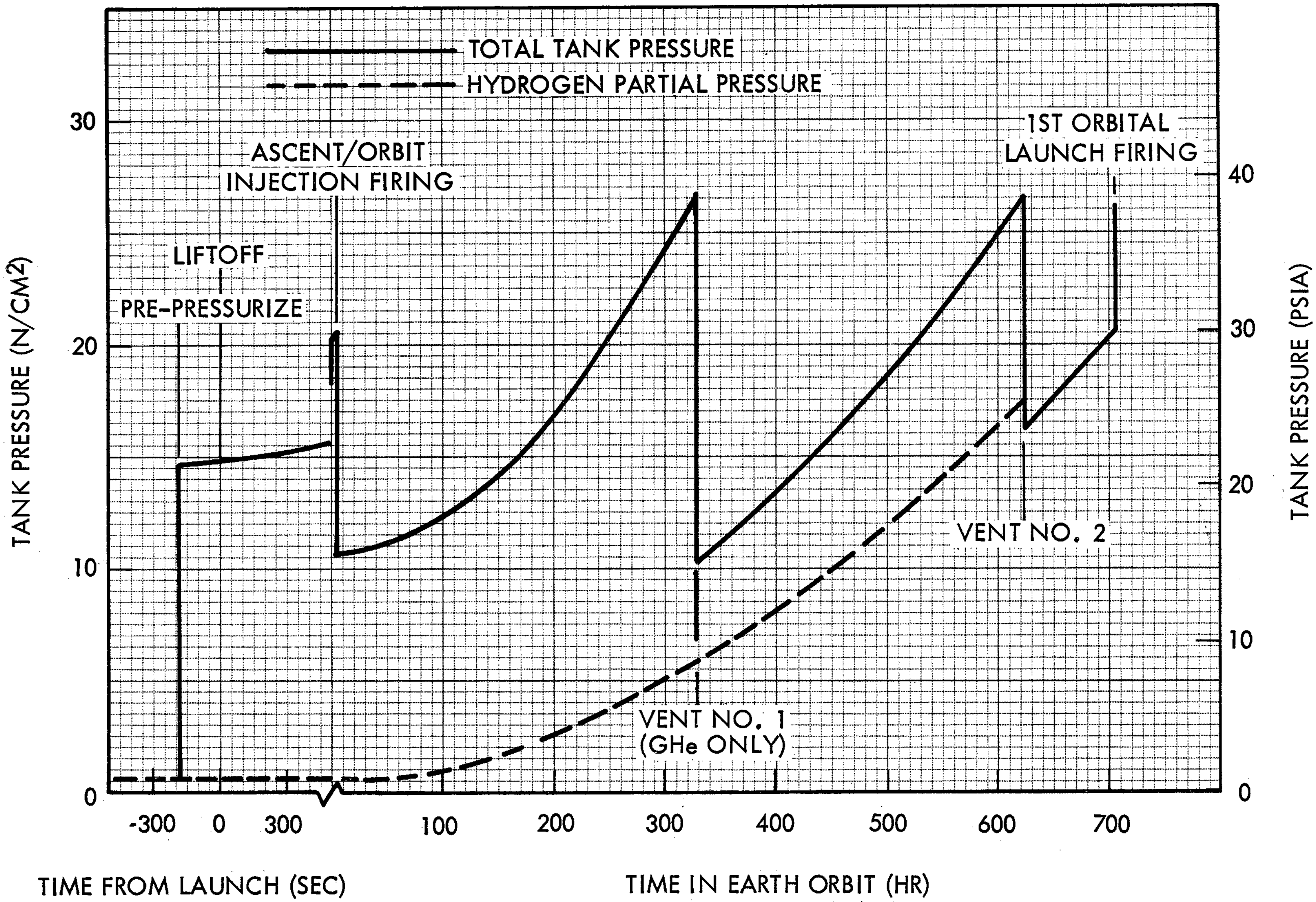

Fig. 2-22 Hydrogen Tank Pressure-Time History for S-IVC$_1$ Stage Fueled With Initially 50-Percent Slush Hydrogen

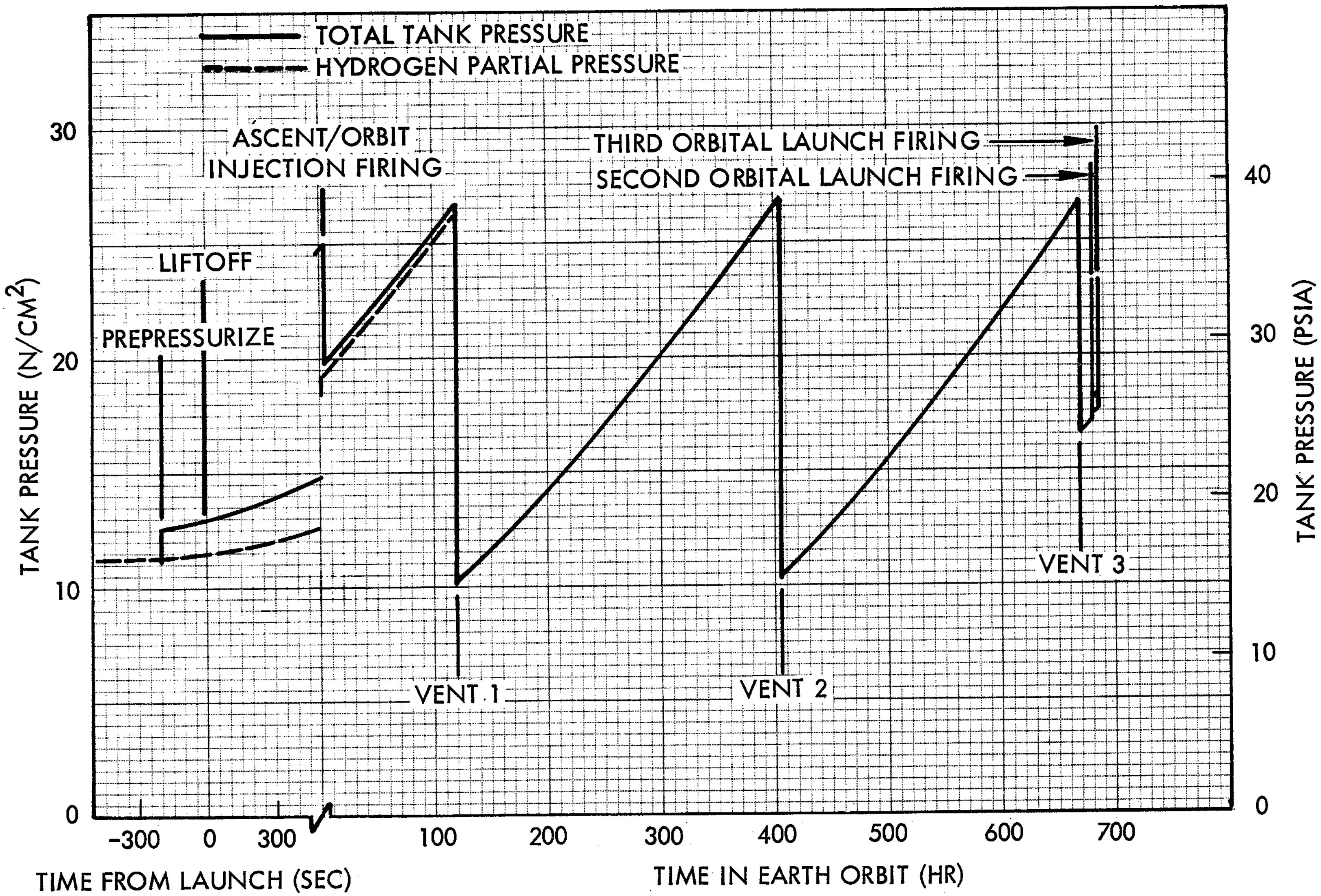

Fig. 2-23 Hydrogen Tank Pressure-Time History for S-IVC$_2$ Stage Fueled With LH_2 Initially Saturated at 11.2 N/cm^2 (16.2 psia)

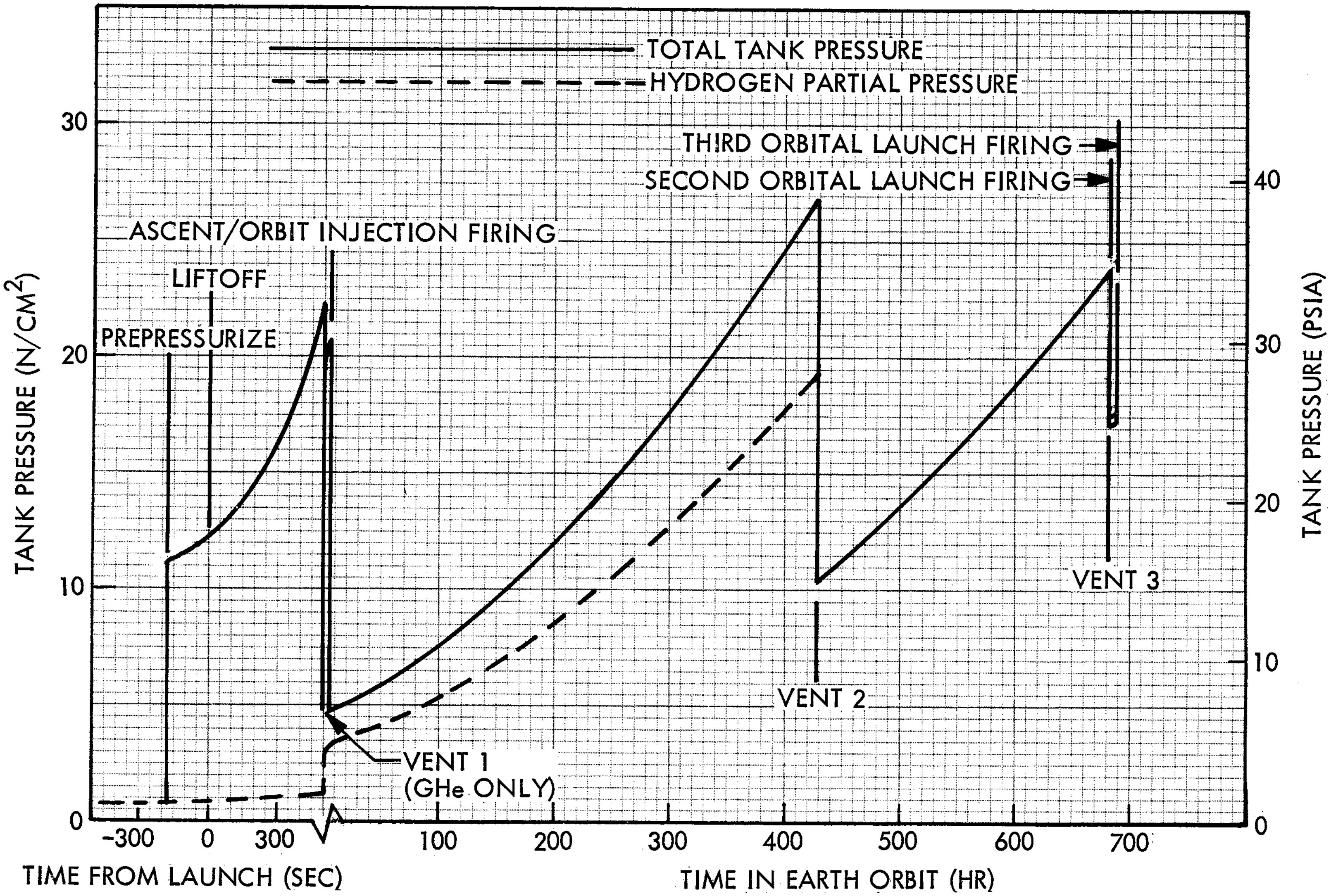

Fig. 2-24 Hydrogen Tank Pressure-Time History for S-IVC$_2$ Stage Fueled With LH$_2$ Initially Saturated at the Triple Point

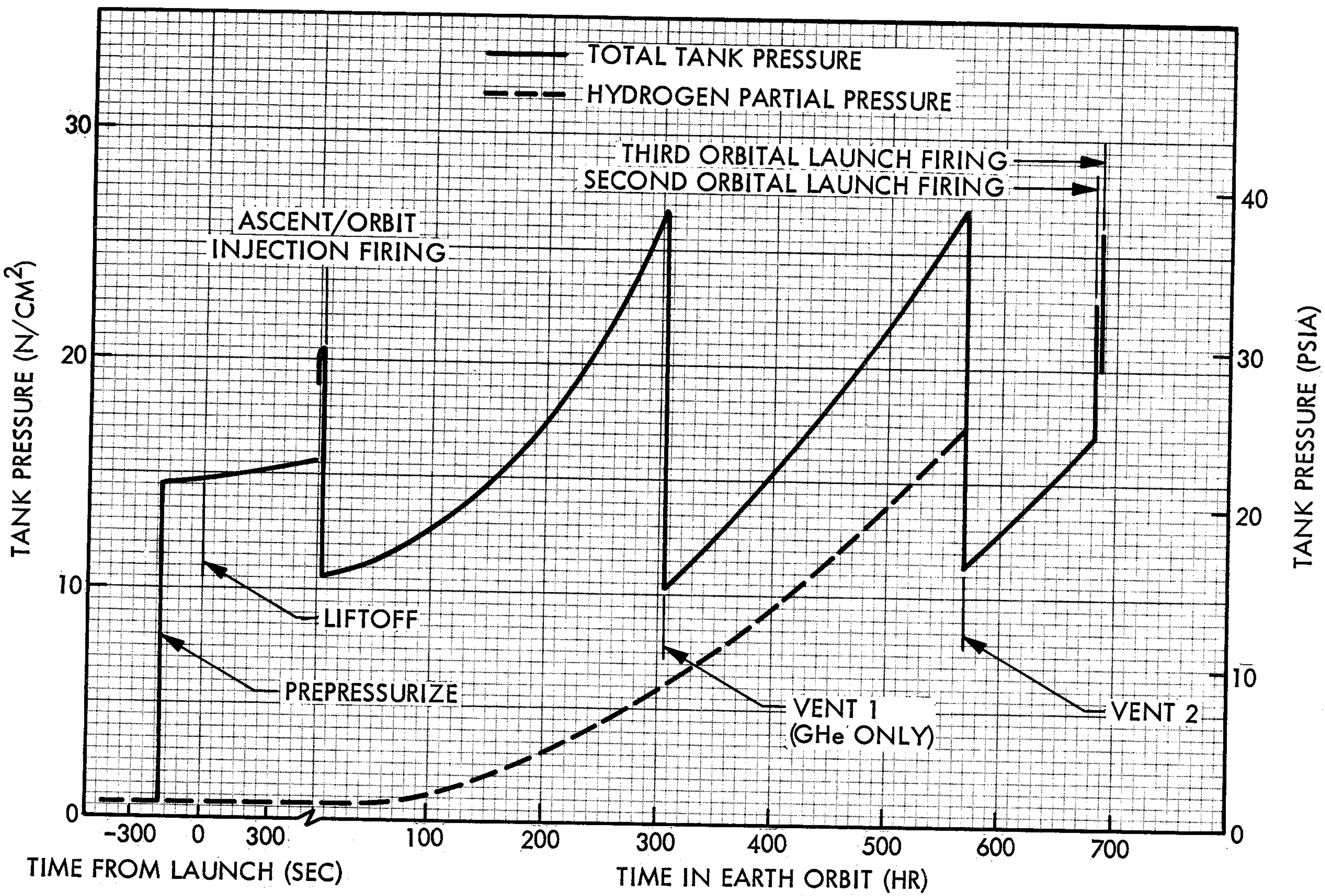

Fig. 2-25 **Hydrogen** Tank Pressure-Time History for S-IVC$_2$ Stage Fueled With Initially 50-Percent Slush Hydrogen

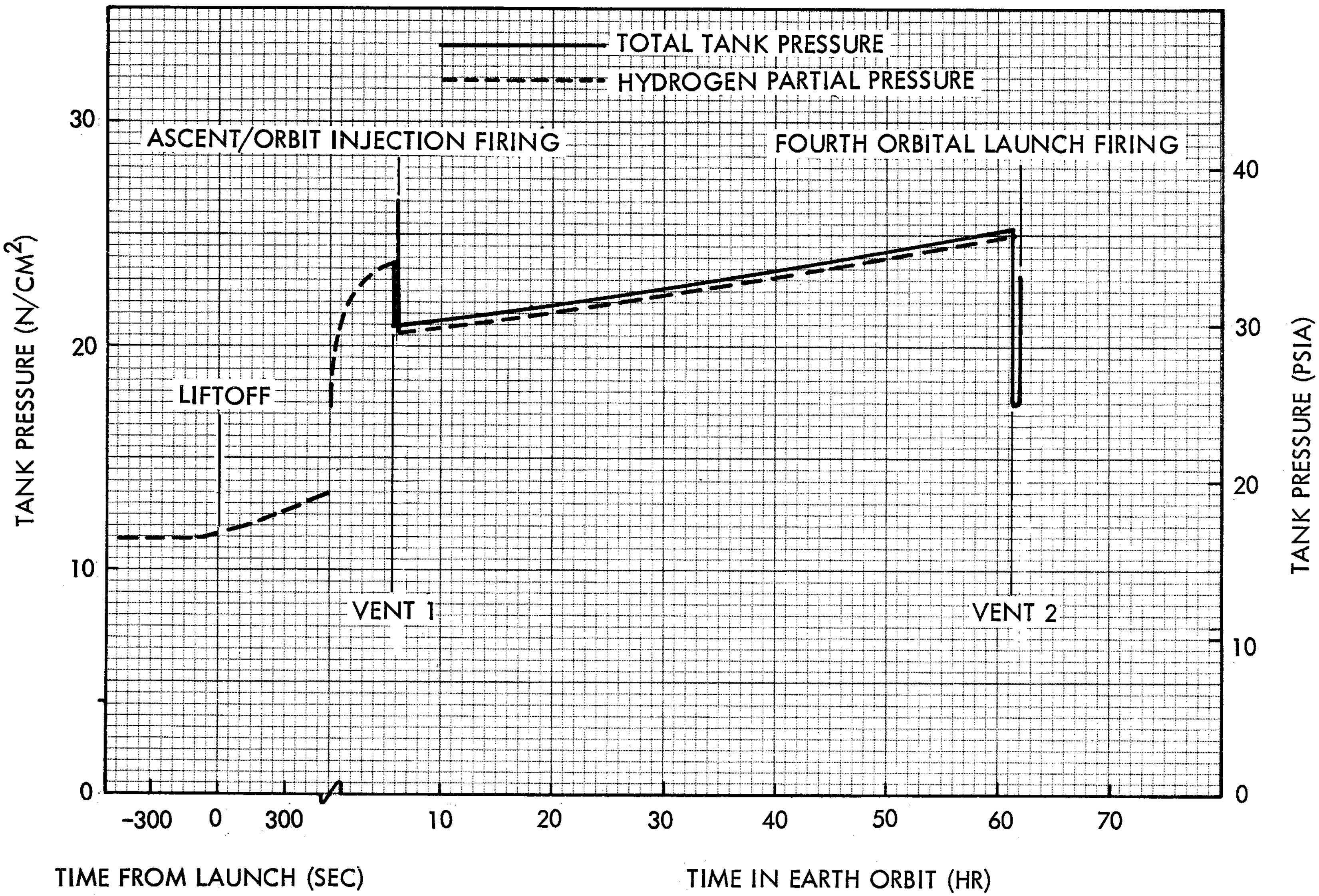

Fig. 2-26 Hydrogen Tank Pressure-Time History for S-IVC$_3$ Stage Fueled With LH$_2$ Initially Saturated at 11.2 N/cm^2 (16.2 psia)

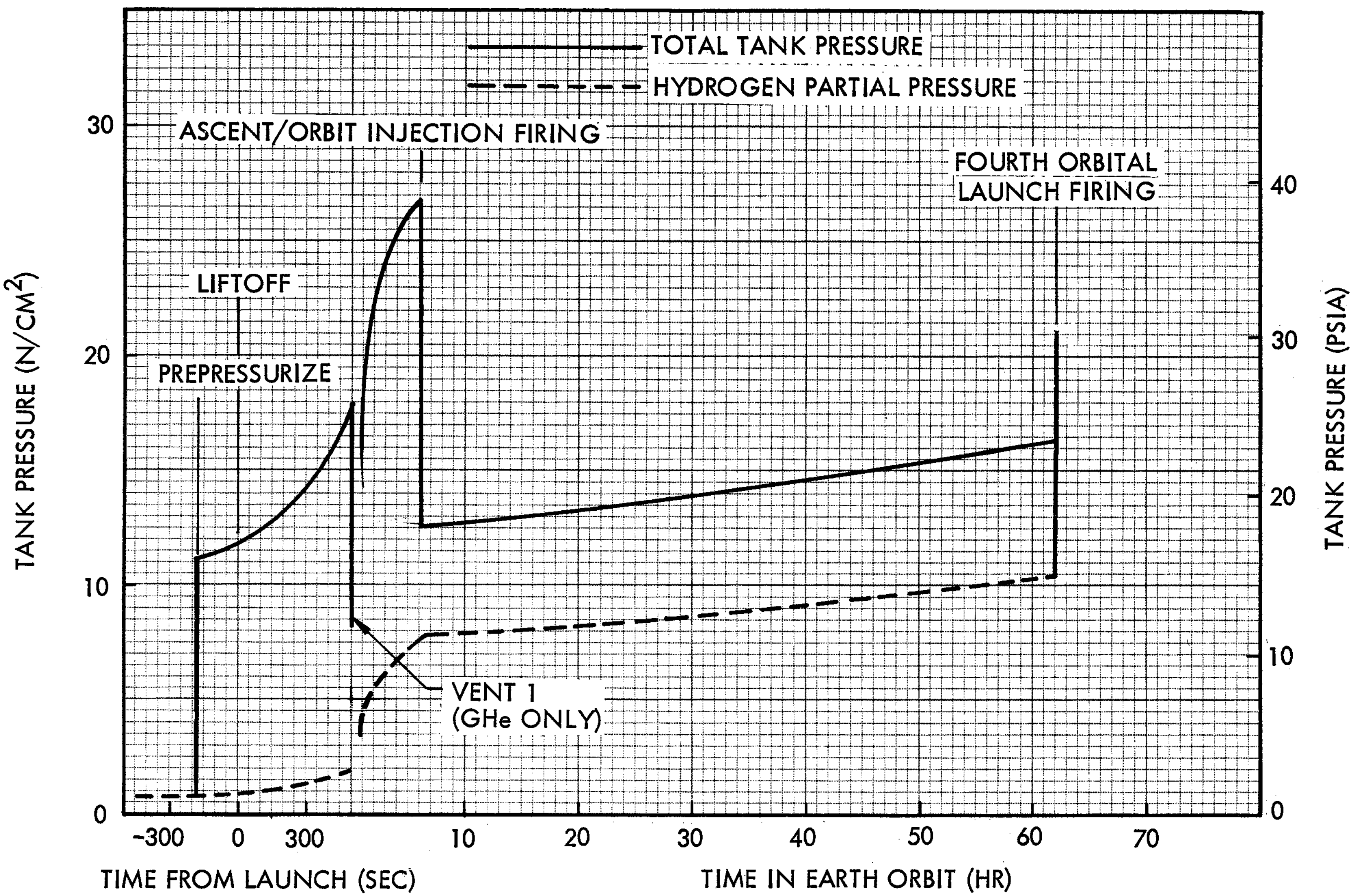

Fig. 2-27 Hydrogen Tank Pressure-Time History for S-IVC$_3$ Stage Fueled With LH$_2$ Initially Saturated at the Triple Point

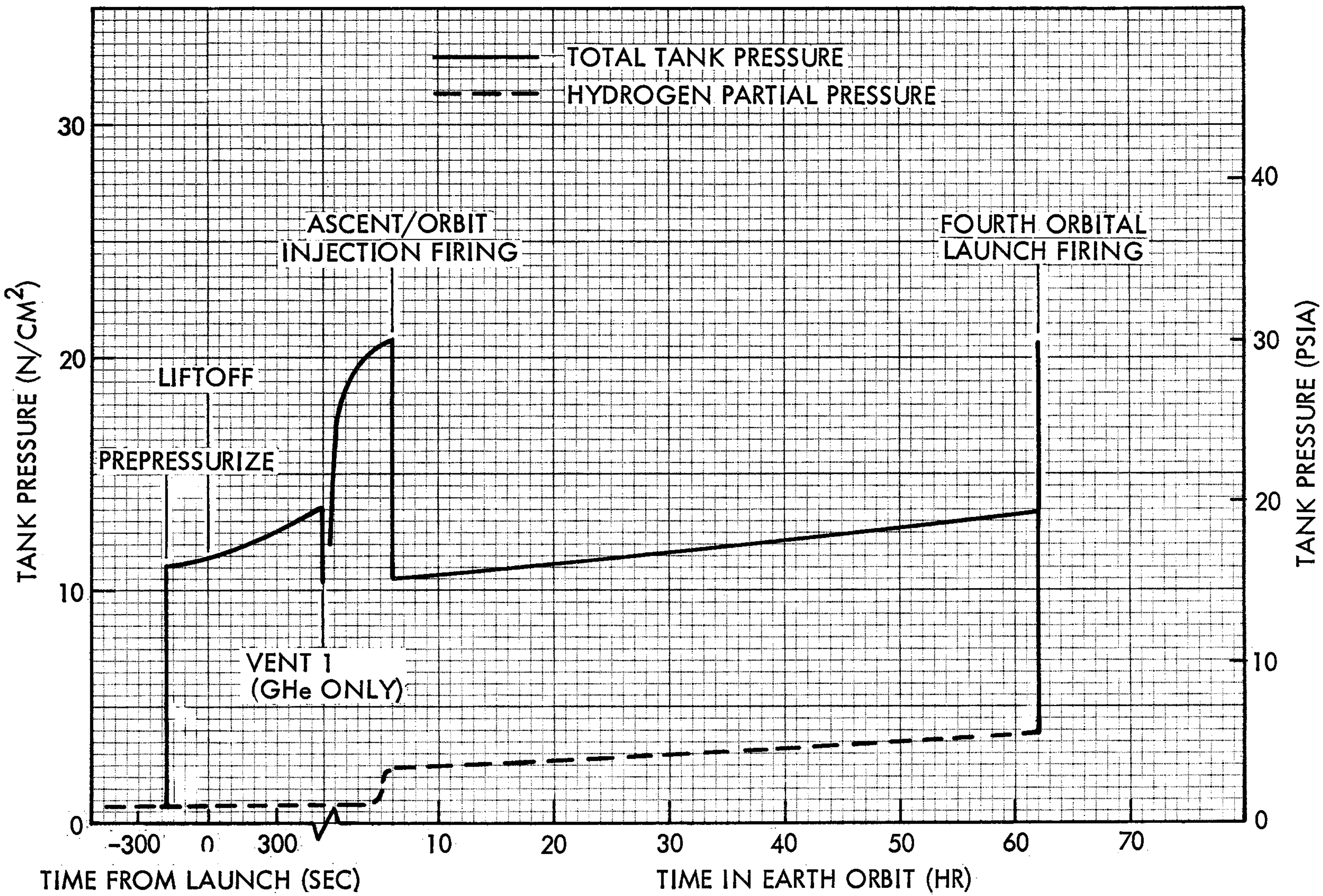

Fig. 2-28 Hydrogen Tank Pressure-Time History for S-IVC$_3$ Stage Fueled With 50-Percent Slush Hydrogen

Table 2-9

SUMMARY OF HYDROGEN TANK VENTING HISTORY

Stage	Initial Hydrogen Condition	Vent No.	Time of Vent (hr)[A]	Mass of H_2 Vented, kg	(lb)
S-IV C_1	LH_2 Sat. at 11.2 N/cm^2 (16.2 psia)	1	70.6	1,551	(3,420)
		2	304.1	1,491	(3,288)
		3	707.0	633	(1,396)
		Total		3,675	(8,104)
	LH_2 Sat. at T.P.	1	366.1	1,052	(2,320)
		2	707.0	434	(957)
		Total		1,486	(3,277)
	50 Percent Liquid-Solid Mixture	1	230.3	Negl.[B]	
		2	623.7	145	(320)
		Total		145	(320)
S-IV C_2	LH_2 Sat. at 11.2 N/cm^2 (16.2 psia)	1	74.0	1,551	(3,420)
		2	278.1	1,505	(3,318)
		3	672.4	850	(1,873)
		Total		3,906	(8,611)
	LH_2 Sat. at T.P.	1	334.3	1,043	(2,300)
		2	683.0	633	(1,396)
		Total		1,676	(3,696)
	50 Percent Liquid-Solid Mixture	1	213.4	Negl.[B]	
		2	450.5	703	(1,549)
		Total		703	(1,549)
S-IV C_3	LH_2 Sat. at 11.2 N/cm^2 (16.2 psia)	1	6.0	280	(617)
		2	62.0	713	(1,572)
		Total		993	(2,189)
	LH_2 Sat. at T.P.	-	-	0	
	50 Percent Liquid-Solid Mixture	-	-	0	

NOTES: [A] Time from liftoff of each particular stage.
[B] Initial vent programmed to blowdown partial pressure of GHe prepressurant; vent terminates at a pressure above H_2 saturation pressure with negligible loss of hydrogen.

the hydrogen could result in weight penalties for additional vents and for increased pressurization gas requirements. Weight penalties associated with these effects can be minimized, however, by using the on-board computer located in the Instrument Unit (I. U.) to monitor and control vent pressure limits so that repressurization requirements for the next firing are within design tolerances. The only significant effect of having additional vent cycles, then, is that associated with increased APS firing requirements to settle the propellants. This effect was calculated during the study in comparing the results of this venting analysis with those obtained by Douglas in their study where the number of vent cycles assumed was much greater*. The comparison is shown below:

Stage:	S-IVC$_1$	S-IVC$_2$	S-IVC$_3$	Total
No. of Vents:				
Lockheed Study:	3	3	2	8
Douglas Study:	37	36	7	80
Difference in APS Propellant Req'd kg (lb):	1069 (2357)	1032 (2276)	51 (112)	2152 (4745)
Equivalent Payload, kg (lb):	442 (975)	589 (1298)	51 (112)	1082 (2385)

During the study, the effect of using a low-gravity vent device that does not require settling of propellants to operate, rather than the cyclic vent mode, was also investigated. It was determined during this analysis that essentially all of the aft module APS propellant assigned to ullaging could be deleted if such a system were used. The additional inert weight required to provide such a system would be approximately 11.3 kg (25 lb) per stage. The net gain in payload for the S-IVC OLV would then be approximately 1172 kg (2584 lb).

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*The Douglas analysis apparently did not assume complete thermal mixing through use of mechanical mixers located in the S-IVC stage hydrogen tanks.

It should be noted in examining the data presented in the tank pressure-time histories (Figs. 2-20 to 2-28) that wherever a particular vent is identified as a "GHe only" vent, the tank pressure at which the vent is terminated is still above the pressure corresponding to liquid hydrogen temperature saturation conditions at that time. It was assumed in the analysis that only gaseous helium is vented overboard during such a cycle since mass boiling of the hydrogen would not have occurred at that pressure.

2.6 PRESSURIZATION SYSTEM

For purposes of this study, it was assumed that gaseous helium would be used to pressurize initially the S-IVC stage propellant tanks to provide net positive suction pressure (NPSP) for main-engine-start cycles; and, in addition, to expel liquid oxygen during the main engine firings. In all cases where such pressurization would be required for the Earth-orbit-injection firing of each of the S-IVC stages, the GHe pressurant would be injected into the tanks from ground facilities just prior to umbilical disconnect at the beginning of the 180-sec prelaunch hold. Expulsion of liquid hydrogen for all main engine firings would be accomplished using warm hydrogen gas bled from the engine after start. The gaseous helium required for LO_2 expulsion and for LH_2 tank repressurization just prior to the OLV firings would be supplied from high-pressure storage spheres mounted inside the LH_2 tank. This GHe would be stored at liquid-and/or slush-hydrogen temperatures, and would then require preheating using an O_2-H_2 burner system (that presently exists on S-IVB/V stages) before injection into the propellant tanks. The general pressurization mode described above as it applies to this study is that in use on existing S-IVB/V stages.

Pressurization system requirements that were determined during the study for the three S-IVC stages are presented in Table 2-10. These requirements are given in the table for S-IVC stages fueled with hydrogen at each of the three initial conditions of interest.

Table 2-10

SUMMARY OF PRESSURIZATION WEIGHT REQUIREMENTS

Pressurization Function	Pressurant	Inlet Temp °K (°R)	Initial Hydrogen Condition: LH_2 Sat. at 11.2 N/cm^2 (16.2 psia) Joules (Btu)	Initial Hydrogen Condition: LH_2 Sat. at T. P. Joules (Btu)	Initial Hydrogen Condition: 50 Percent Liquid-Solid Mixture Joules (Btu)
S-IV C_1 Stage:					
Prepressurization[A]	GHe	B	0.226×10^6 (210)	3.449×10^6 (3,270)	11.149×10^6 (10,570)
Expulsion for Ascent Firing	GH_2	111 (200)	31.686×10^6 (30,040)	24.071×10^6 (22,820)	23.100×10^6 (21,900)
Repressurization	GHe	139 (250)	9.905×10^6 (9,390)	3.502×10^6 (3,320)	2.215×10^6 (2,100)
Expulsion for OLV Firing	GH_2	111 (200)	178.7×10^6 (169,460)	232.1×10^6 (220,000)	278.5×10^6 (264,000)
Totals			220.5×10^6 (209,100)	263.1×10^6 (249,410)	315.0×10^6 (298,570)
S-IV C_2 Stage:					
Prepressurization[A]	GHe	B	0.386×10^6 (370)	3.481×10^6 (3,300)	10.622×10^6 (10,070)
Expulsion for Ascent Firing	GH_2	111 (200)	31.581×10^6 (29,940)	24.071×10^6 (22,820)	23.100×10^6 (21,900)
Repressurization	GHe	139 (250)	10.432×10^6 (9,890)	3.776×10^6 (3,580)	2.542×10^6 (2,410)
Expulsion for 1st OLV Firing	GH_2	111 (200)	44.238×10^6 (41,940)	58.130×10^6 (55,110)	60.567×10^6 (57,420)
Repressurization	GHe	139 (250)	13.776×10^6 (13,060)	9.799×10^6 (9,290)	9.335×10^6 (8,850)
Expulsion for 2nd OLV Firing	GH_2	111 (200)	135.1×10^6 (128,050)	176.3×10^6 (167,100)	182.4×10^6 (172,890)
Totals			235.5×10^6 (223,250)	275.6×10^6 (261,200)	288.6×10^6 (273,540)
S-IV C_3 Stage:					
Prepressurization[A]	GHe	C	1.171×10^6 (1,110)	8.048×10^6 (7,630)	10.390×10^6 (9,850)
Expulsion for Ascent Firing	GH_2	111 (200)	33.616×10^6 (31,870)	32.140×10^6 (30,470)	23.807×10^6 (22,570)
Repressurization	GHe	139 (250)	6.223×10^6 (5,900)	3.059×10^6 (2,900)	6.118×10^6 (5,800)
Expulsion for OLV Firing	GH_2	111 (200)	215.5×10^6 (204,330)	211.9×10^6 (200,890)	203.4×10^6 (192,800)
Totals			256.5×10^6 (243,210)	255.1×10^6 (241,890)	243.7×10^6 (231.020)

NOTES:

[A] Prepressurants injected prior to liftoff; except the S-IVC stage when fueled with LH_2 saturation at 11.2 N/cm^2 (16.2 psia).
[B] 20.7°K (37.2°R) for LH_2 saturation at 11.2 N/cm^2 (16.2 psia); 13.8°K (24.9°R) for LH_2 saturation at triple point and 50 percent liquid-solid mixture.
[C] 139°K (250°R) for LH_2 saturation at 11.2 N/cm^2 (16.2 psia); 13.8°K (24.9°K) for LH_2 saturation at triple point and 50 percent liquid-solid mixture.

2.7 PERFORMANCE ANALYSIS

A preliminary performance analysis was conducted early in the study to determine optimum S-IVC stage ignition weights, propellant loadings, and mixture ratios. Using results of this preliminary performance analysis, the insulation, venting, and pressurization system analyses described in previous sections were conducted. The performance analysis was then finalized using results of the various system analyses. A summary of the vehicle ignition weights, velocity increments, engine mixture ratios, and specific impulse values that resulted was presented earlier (Table 2-7).

The relationship of total tanked hydrogen weight to percent ullage volume is shown in Figs. 2-29 through 2-31 for each of the three S-IVC stages fueled with hydrogen at each initial condition of interest. The maximum hydrogen loading limits used in performing the analysis during the study were determined from the data presented in the figures so that the net ullage volume in the hydrogen tanks did not decrease below approximately 2 percent at first engine ignition. Tanked propellant weights used in performing the final analysis were previously presented (Tables 2-2 and 2-3).

Results of the final OLV performance analysis is presented in Fig. 2-32. The data shown in the figure were determined by calculating the total impulse velocity increments that would be achieved with the four OLV firings previously described assuming a range of payload spacecraft weights. These data were then plotted, and the particular payload weights that correspond to the 1975 Mars twilight flyby mission velocity requirement are shown on the figure for OLV stages fueled with hydrogen at each initial condition of interest. It should be noted that throughout the study use of a particular initial hydrogen condition was assumed in all three S-IVC stages of that particular OLV when each stage was launched from Earth.

A summary of OLV weights that would exist at each significant mission milestone resulting from the final performance analysis is presented in Table 2-11.

Estimated dry stage inert weights used throughout the study are presented in Table 2-12. These weights include those used for each of the three S-IVC stages fueled with hydrogen at each initial condition of interest.

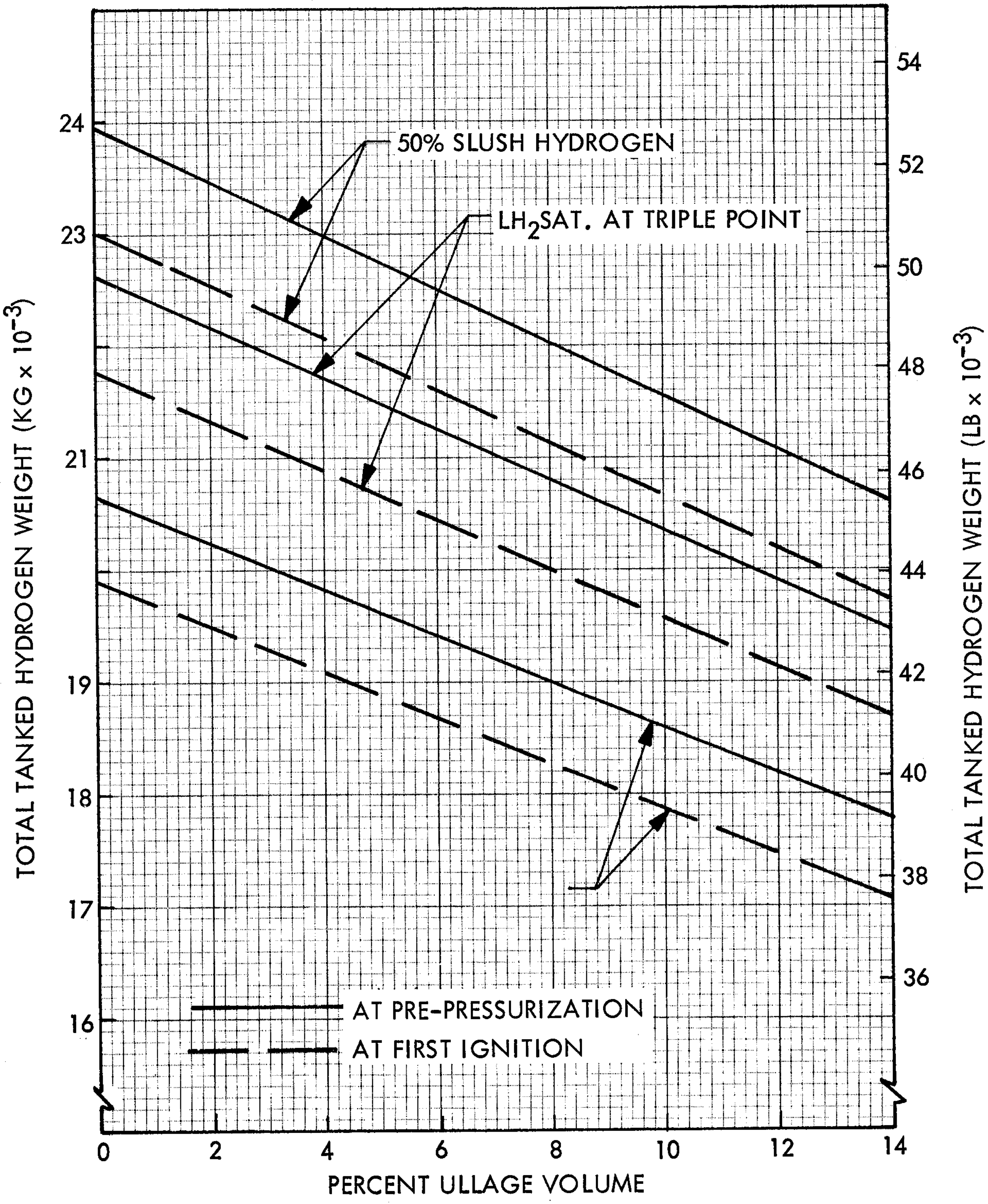

Fig. 2-29 Total Tanked Hydrogen Weight As a Function of Percent Ullage Volume for the S-IVC$_1$ Stage

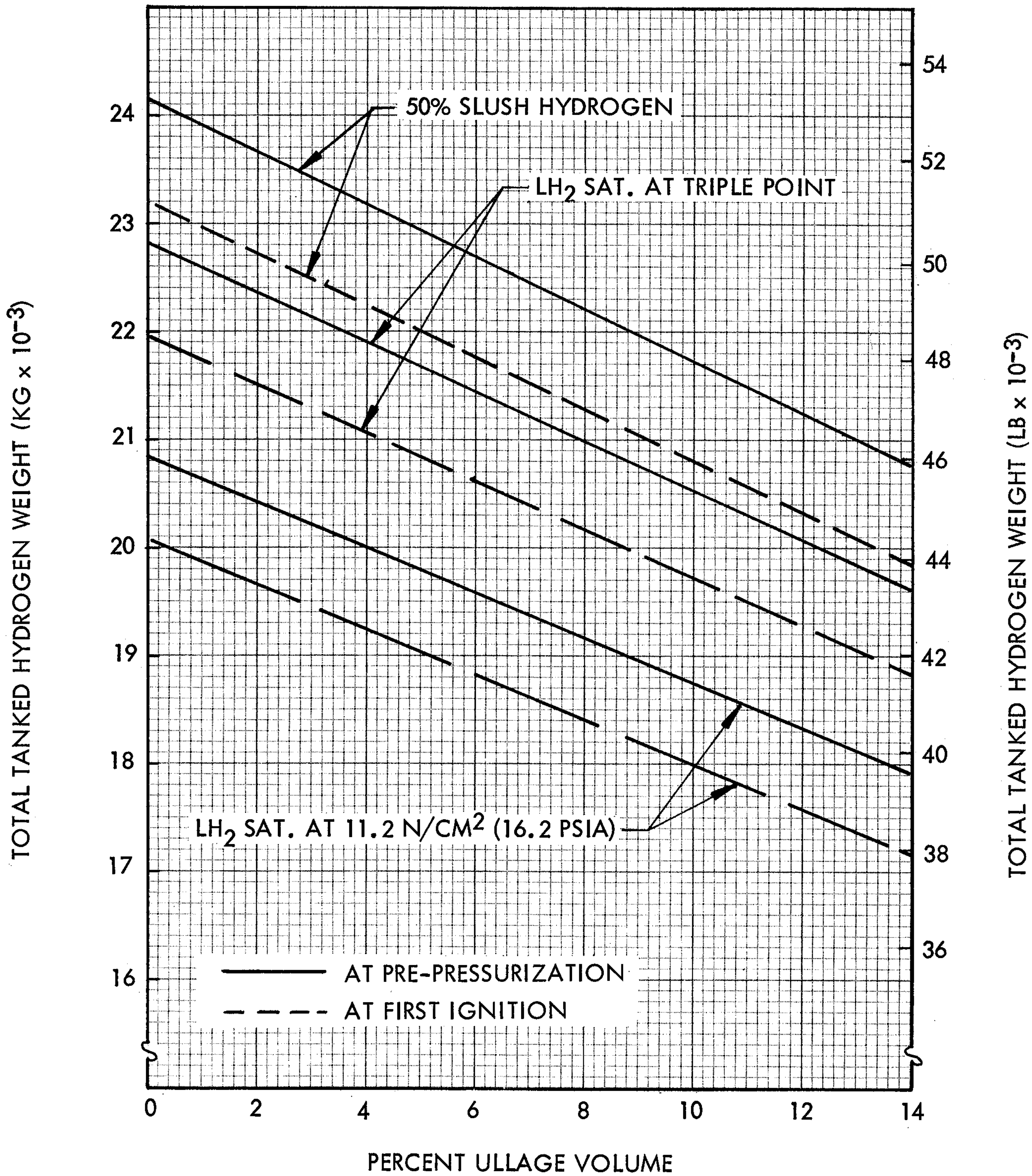

Fig. 2-30 Total Tanked Hydrogen Weight As a Function of Percent Ullage Volume for the S-IVC$_2$ Stage

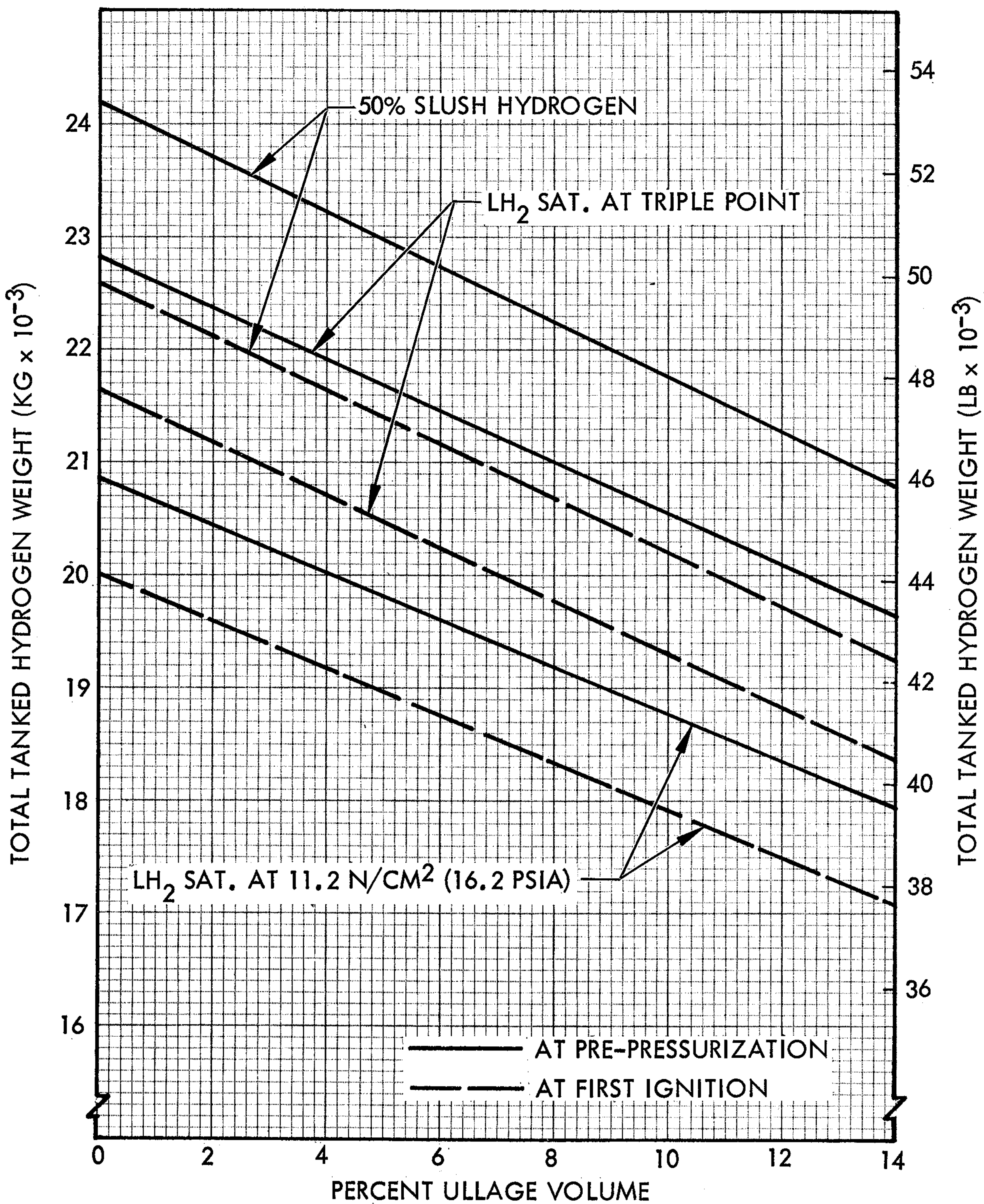

Fig. 2-31 Total Tanked Hydrogen Weight As a Function of Percent Ullage Volume for the S-IVC$_3$ Stage

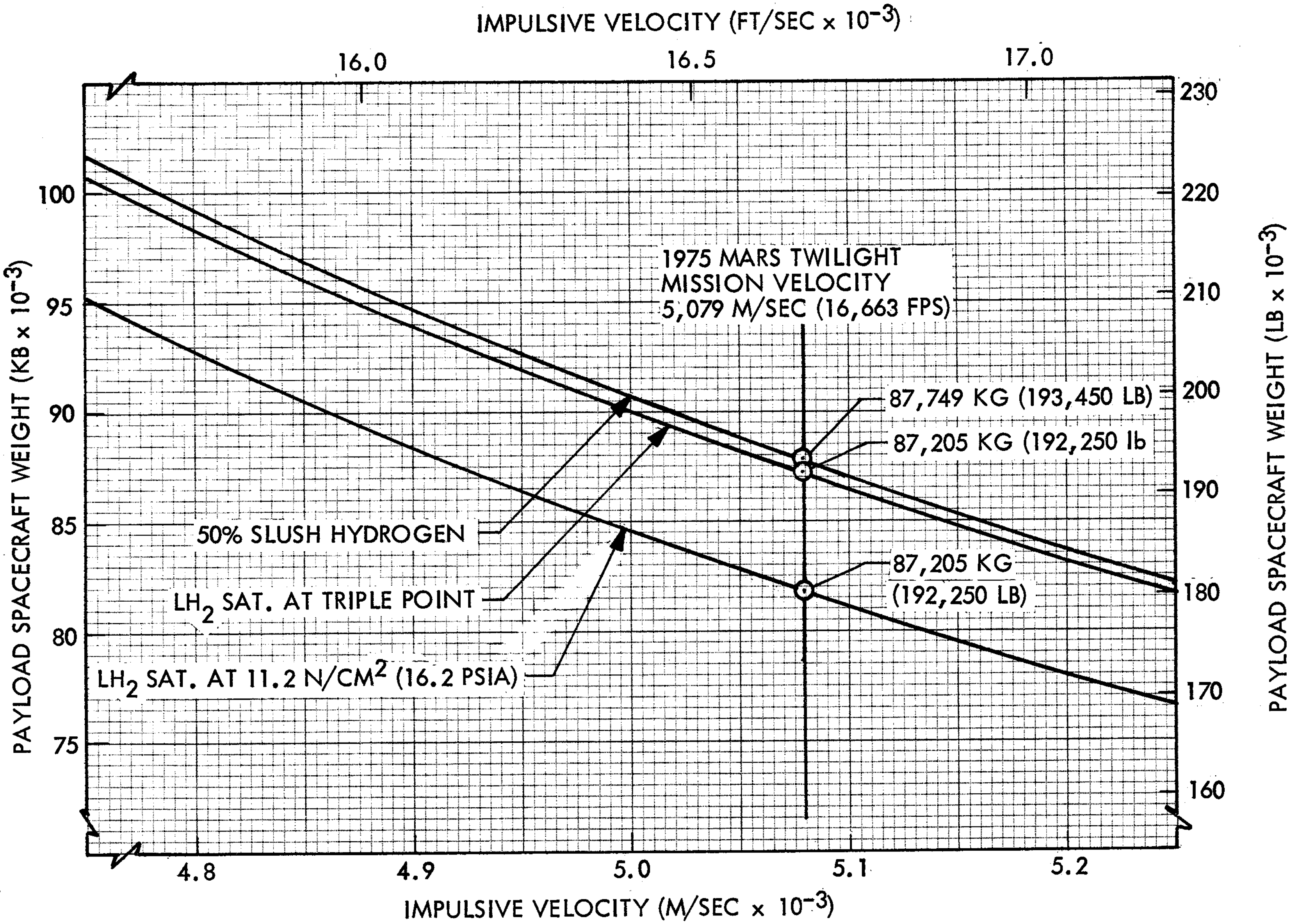

Fig. 2-32 S-IVC Orbital Launch Vehicle Performance As a Function of Impulsive Velocity and Initial Hydrogen Condition

Table 2-11

SUMMARY OF PERFORMANCE WEIGHTS

Weight Description	Initial Hydrogen Condition											
	LH2 Sat. at 11.2 N/cm^2 (16.2 psia)				LH2 Sat. at T.P.				50 Percent Liquid-Solid Mixture			
	S-IV C_1 kg (lb)	S-IV C_2 kg (lb)	S-IV C_3 kg (lb)	Total kg (lb)	S-IV C_1 kg (lb)	S-IV C_2 kg (lb)	S-IV C_3 kg (lb)	Total kg (lb)	S-IV C_1 kg (lb)	S-IV C_2 kg (lb)	S-IV C_3 kg (lb)	Total kg (lb)
Gross Earth-Launch Weight	121,111 (267,000)	119,969 (264,482)	121,111 (267,000)	362,191 (798,482)	121,111 (267,000)	121,111 (267,000)	121,111 (267,000)	363,333 (801,000)	121,111 (267,000)	121,111 (267,000)	121,111 (267,000)	363,333 (801,000)
Less Weights Jettisoned in Earth Orbit	19,179 (42,281)	19,356 (42,672)	13,471 (29,698)	52,006 (114,651)	16,656 (36,719)	16,792 (37,019)	12,365 (27,259)	45,813 (100,997)	15,461 (34,084)	15,954 (35,172)	12,348 (27,223)	43,763 (96,479)
Plus Payload Spacecraft Weight				81,920 (180,600)				87,205 (192,250)				87,749 (193,450)
Gross Orbital Launch Weight				392,105 (864,431)				404,725 (892,253)				407,320 (897,971)
Less Transients and Settling Propellant	459 (1,013)			459 (1,013)	459 (1,013)			459 (1,013)	459 (1,013)			459 (1,013)
First OLV Firing Initial Weight				391,646 (863,418)				404,266 (891,240)				406,860 (896,958)
Less 1st OLV Firing Impulse Propellant Weight	83,394 (183,850)			83,394 (183,850)	85,927 (189,434)			85,927 (189,434)	87,091 (191,999)			87,091 (191,999)
First OLV Firing Burnout Weight				308,252 (679,568)				318,339 (701,806)				319,769 (704,959)
Less Jettisoned Weights	18,079 (39,856)	459 (1,013)		18,538 (40,869)	18,069 (39,834)	459 (1,013)		18,528 (40,847)	18,100 (39,904)	459 (1,013)		18,559 (40,917)
Second OLV Firing Initial Weight				289,714 (638,699)				299,811 (660,959)				301,209 (664,042)
Less 2nd OLV Firing Impulse Propellant Weight		20,446 (45,076)		20,446 (45,076)		21,375 (47,124)		21,375 (47,124)		21,590 (47,596)		21,590 (47,596)
Second OLV Firing Burnout Weight				269,268 (593,623)				278,436 (613,835)				279,620 (616,446)
Less Transients and Settling Propellant		459 (1,013)		459 (1,013)		459 (1,013)		459 (1,013)		459 (1,013)		459 (1,013)
Third OLV Firing Initial Weight				268,809 (592,610)				277,977 (612,822)				279,160 (615,433)
Less 3rd OLV Firing Impulse Propellant Weight		61,339 (135,228)		61,339 (135,278)		64,127 (141,373)		64,127 (141,373)		64,770 (142,790)		64,770 (142,790)
Third OLV Firing Burnout Weight				207,470 (457,382)				213,850 (471,449)				214,391 (472,643)
Less Jettisoned Weights		17,910 (39,480)	459 (1,013)	18,369 (40,493)		17,899 (39,458)	459 (1,013)	18,358 (40,471)		17,880 (39,416)	459 (1,013)	18,339 (40,429)
Fourth OLV Firing Initial Weight				189,101 (416,889)				195,492 (430,978)				196,052 (432,214)
Less 4th OLV Firing Impulse Propellant Weight			89,956 (198,316)	89,956 (198,316)			91,234 (201,134)	91,234 (201,134)			91,147 (200,941)	91,147 (200.941)
Fourth OLV Firing Burnout Weight				99,145 (218,573)				104,258 (229,844)				104,905 (231,273)
Less S-IV C_3 Burnout Weight			17,225 (37,973)	17,225 (37,973)			17,053 (37,594)	17,053 (37,594)			17,157 (37,823)	17,157 (37,823)
Spacecraft Payload Weight				81,920A (180,600)				87,205 (192,250)				87,749 (193,450)
Increase in Spacecraft Payload Weight								5,284 (11,650) [6.45%]				5,829 (12,850) [7.12%]

A Reference case.

Table 2-12

ESTIMATED DRY STAGE INERT WEIGHTS

Item Description	Ref. Source	LH_2 Sat. at 11.2 N/cm^2 (16.2 psia) kg (lb)		LH_2 Sat. at Triple Point lb (lb)		50% Liquid-Solid Mixture kb (lb)	
Dry Stage (SA 504 and subsequent) Removed:	Douglas Report DAC-57997	11,284	(24,876)	Same as for LH_2 Sat. at 11.2 N/cm^2 (16.2 psia)		Same as for LH_2 Sat. at 11.2 N/cm^2 (16.2 psia)	
Batteries and Mounts		-376	(-830)				
APS Modules		-388	(-855)				
Ullage Rockets		-91	(-200)				
Chilldown and Purge Systems		-130	(-287)				
Miscellaneous Engine Systems		-22	(-48)				
Internal Insulation		-629	(-1,386)				
Add Common Structure and Equipment Modifications:							
Aft Skirt APS Modifications		+36	(+80)				
J-2S Engine		-112	(-246)				
Forward Heat Block		+106	(+233)				
Power System		+1,557	(+3,432)				
Common Dome Heat Block		+12	(+26)				
Forward Docking Structure		+772	(+1,702)				
Aft Docking Structure		+604	(+1,332)				
Forward Dome External Insulation		+34	(+74)				
Aft Dome Insulation		+4	(+9)				
Common-Modification Dry-Stage Weight		12,661	(27,912)	12,661	(27,912)	12,661	(27,912)
Add S-IVC$_1$ Modifications:	Present Lockheed Study						
External Insulation and Meteoroid Bumper		+885	(+1,950)	+885	(+1,950)	+885	(+1,950)
Common Bulkhead Insulation		+653	(+1,440)	+653	(+1,440)	+653	(+1,440)
Additional Instrumentation and Wiring		0		+9	(+20)	+41	(+90)
Liquid-Return Line, Valve, and Disconnect		0		+32	(+70)	+32	(+70)
Hydrogen Tank Pressurization System Reqmts.		-65	(-144)	-98	(-216)	-98	(-216)
Total Modified S-IVC$_1$ Dry-Stage Weight		14,134	(31,158)	14,142	(31,176)	14,174	(31,246)
Add S-IVC$_2$ Modifications:							
External Insulation and Meteoroid Bumper		+885	(+1,950)	+885	(+1,950)	+885	(+1,950)
Common Bulkhead Insulation		+381	(+840)	+381	(+840)	+381	(+840)
Additional Instrumentation and Wiring		0		+9	(+20)	+41	(+90)
Liquid-Return Line, Valve, and Disconnect		0		+32	(+70)	+32	(+70)
Hydrogen Tank Pressurization System Reqmts.		0		-33	(-72)	-65	(-144)
Total Modified S-IVC$_2$ Dry-Stage Weight		13,927	(30,702)	13,935	(30,720)	13,935	(30,718)
Add S-IVC$_3$ Modifications:							
External Insulation and Meteoroid Bumper		+599	(+1,321)	+473	(+1,043)	+473	(+1,043)
Common Bulkhead Insulation		+87	(+192)	0		0	
Additional Instrumentation and Wiring		0		+9	(+20)	+41	(+90)
Liquid-Return Line, Valve, and Disconnect		0		+32	(+70)	+32	(+70)
Hydrogen Tank Pressurization System Reqmts.		-65	(-144)	-98	(-216)	-98	(+216)
Total Modified S-IVC$_3$ Dry-Stage Weight		13,282	(29,281)	13,077	(28,829)	13,109	(28,899)

The final performance analysis data (Fig. 2-32) show that the manned spacecraft weight can be increased by approximately 5285 kg (11,650 lb) when the three OLV stages are initially fueled with triplepoint liquid hydrogen rather than liquid saturated at 11.2 N/cm^2 (16.2 psia). This is equivalent to a 6.45 percent increase in the reference spacecraft weight of 81,920 kg (180,600 lb) for the saturated LH_2-fueled OLV.

Further, when 50-percent slush is initially loaded into the three OLV stages, the manned spacecraft weight can be increased by approximately 5829 kg (12,850 lb) or 7.12 percent over that of the reference OLV fueled with saturated LH_2.

Section 3

REFERENCES

1-1 Lockheed Report K-11-67-1, "Final Report – A Study of Hydrogen Slush and/on Hydrogen Gel Utilization," Vol. II, Section 3, March 1967

2-1 DAC Report 57997, "Feasibility of Modifying the S-IVB Stage as an Injection Stage for Manned Planetary Flyby Missions," 2 Volumes, R. S. Cowls et. al., May 1967

2-2 Lockheed Report K-11-67-1, Vol. II, Subsection 3.2

2-3 Lockheed Report K-11-67-1, Vol. II, Subsection 2.2.1.1, Equation (2.4)

2-4 Lockheed Report K-11-67-1, Vol. II, Subsections 2.2.2 and 3.2.2

2-5 Lockheed Report K-11-67-1, Vol. II, Subsection 3.2.3

2-6 NAA/SID Report 67-275-2, "Final Report, Feasibility of Modifying the S-II Stage as an Injection Stage for Manned Planetary Flyby Missions," Vol. II, Section IX, W. H. Morita et. al., March 1967

2-7 DAC Report 57997, Vol. II, Subsection 5.2

2-8 GAC Report GER 11676 S/36, Annual Summary Report, June 1967

2-9 Lockheed Report K-11-67-1, Vol. II, Subsection 3.4.2.2

2-10 DAC Report 57997, Vol. II, Subsection 5.3

2-11 Lockheed Report K-11-67-1, Vol. II, Subsection 2.5

Section 4

CONVERSION FACTORS

Multiply	By	To Obtain
Atmospheres (atm)	10.1325	Newtons per square centimeter (N/cm^2)
Atmospheres (atm)	14.6959	Pounds force per square inch (psi)
British thermal units (Btu)	1054.8	Joules (Joule)
Btu per hour (Btu/hr)	0.292833	Watts (w)
Btu per hour-foot-°R (Btu/hr-ft-°R)	1.731×10^{-2}	Watts per centimeter-°K (w/cm-°K)
Btu per pound (Btu/lb)	2.32597	Joules per gram (Joule/gm)
Centimeters (cm)	0.3937	Inches (in.)
Cubic feet (ft^3)	0.02832	Cubic meters (m^3)
Cubic feet (ft^3)	7.481	Gallons (gal)
Cubic meters (m^3)	35.31	Cubic feet (ft^3)
Cubic meters (m^3)	264.2	Gallons (gal)
Degrees Kelvin (°K)	1.8	Degrees Rankine (°R)
Degrees Rankine (°R)	0.556	Degrees Kelvin (°K)
Feet (ft)	0.3048	Meters (m)
Gallons (gal)	0.1337	Cubic feet (ft^3)
Gallons (gal)	3.785×10^{-3}	Cubic meters (m^3)
Inches (in.)	2.540	Centimeters (cm)
Inches (in.)	2.540×10^{-2}	Meters (m)
Joules (Joule)	9.481×10^{-4}	British thermal units (Btu)
Joules per gram (Joule/gm)	0.42993	Btu per pound (Btu/lb)
Kilograms (kg)	2.205	Pounds mass (lb or lbm)
Kilograms per cubic meter (kg/m^3)	6.243×10^{-2}	Pounds mass per cubic foot (lb/ft^3)
Kilometers (km)	0.539593	Nautical miles (nm)
Meters (m)	3.281	Feet (ft)
Meters (m)	39.37	Inches (in.)
Meters per second (m/sec)	0.101895	Pounds force-seconds per pound mass (lbf-sec/lbm)
Millimeters (mm)	39.37	Mils (mil)
Millimeters of Mercury (mm Hg or torr)	1.934×10^{-2}	Pounds force per square inch (psi)
Mils (mil)	2.540×10^{-2}	Millimeters (mm)
Nautical miles (nm)	1.85325	Kilometers (km)
Newtons (N)	0.2248	Pounds force (lbf)
Newtons per square cm (N/cm^2)	9.869×10^{-2}	Atmospheres (atm)
Newtons per square cm (N/cm^2)	1.450	Pounds force per square in. (psi)
Pounds force (lbf)	4.448	Newtons (N)
Pounds force-seconds per pound mass (lbf-sec/lbm)	9.814	Meters per second (m/sec)
Pounds mass (lb or lbm)	0.4536	Kilograms (kg)
Pounds mass per cubic foot (lb/ft^3)	16.02	Kilograms per cubic meter (kg/m^3)
Pounds force per square inch (psi)	6.804×10^{-2}	Atmospheres (atm)
Pounds force per square inch (psi)	0.6895	Newtons per square cm (N/cm^2)
Pounds force per square inch (psi)	51.7	Millimeters of Mercury (mm Hg or torr)
Watts (w)	3.4152	Btu per hour (Btu/hr)
Watts per centimeter-°K (w/cm-°K)	57.78	Btu per hour-foot-°R (Btu/hr-ft-°R)